Stratigraphic Framework for Basin-Margin, Sub-Unconformity Diagenesis Below the Acadian Unconformity in the Southern Williston Basin*

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Abstract

The Acadian discontinuity is represented by a late Devonian (Famennian) unconformity that lies on top of the Famennian Three Forks Formation in the central portion of the Williston Basin and on truncated Devonian through Cambrian formations in basin-margin areas. Bakken-Pronghorn sediments were deposited in the basin-center and onlap the Acadian unconformity. A maximum flooding surface overlies the Bakken-Pronghorn system in the basin-center but this surface overlies the Acadian unconformity in basin-margin areas. The maximum flooding surface is overlain regionally by open-marine carbonate strata of the basal Lodgepole.

Sub-unconformity diagenesis was an important process in basin-margin areas around the southern Williston Basin; however, the diagenetic analysis in this study focuses on a portion of the southwest Williston Basin where good core data and numerous GR-neutron-density logs are present. Basin-margin, shallow-burial diagenesis beneath the Acadian unconformity formed a paleokarst characterized by evaporite dissolution and massive dolomitization. This diagenesis is illustrated in the Duperow and Birdbear formations, which consist of stratiform limestone, dolostone, and anhydrite beds in the basin-center. These layered lithologies transition to massive dolostone in subcrop areas beneath the Acadian unconformity. A sub-unconformity paleo-dissolution front extends as much as 50 m below the unconformity and former anhydrite beds are now represented by solution-breccia beds within the dissolution area. Massive dolostone cuts across stratigraphic units and extends as much as 70 m below the Acadian unconformity.

While they overlapped in basin-margin areas, massive dolomitization was not related to the fresh-water processes that produced evaporite dissolution during paleokarst formation. Since the massive dolomitization front is sub-parallel to the unconformity over large areas and there is no massive dolostone in overlying basal Lodgepole beds, it is likely that dolomitization occurred after unconformity development and before Lodgepole deposition. This indicates that basin-margin dolomitization took place while Bakken-Pronghorn sediments were being deposited, 10-20 million years after deposition of the Birdbear and Duperow. Basin-margin massive dolomitization probably occurred during one or more evaporative events that caused regional dolomitization within carbonates of the Middle Bakken. The "massive" characteristics, defined by the absence of a stratiform geometry, relate to dolomitization that occurred after mineral stabilization and initial lithification within the Duperow and Birdbear.

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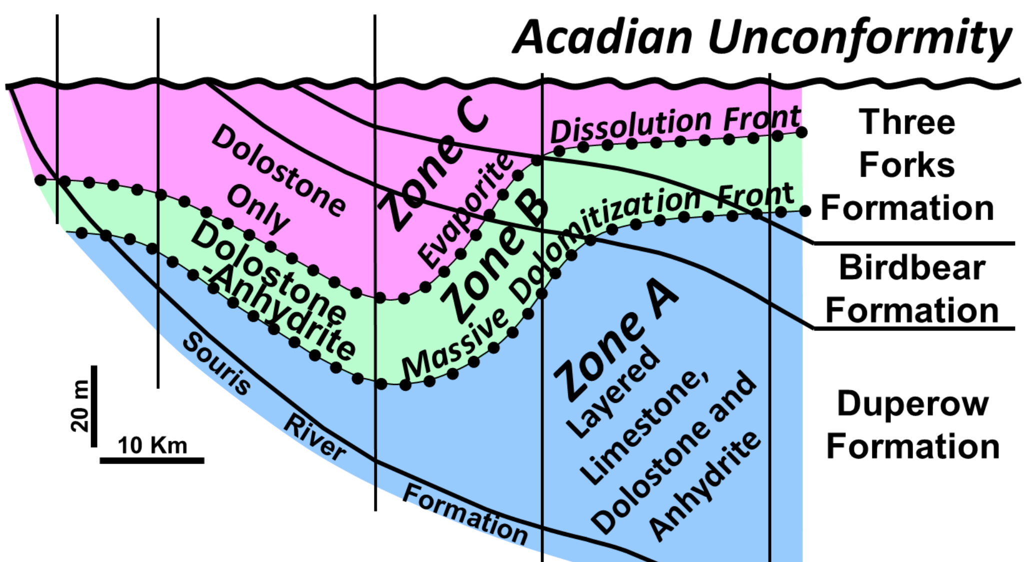
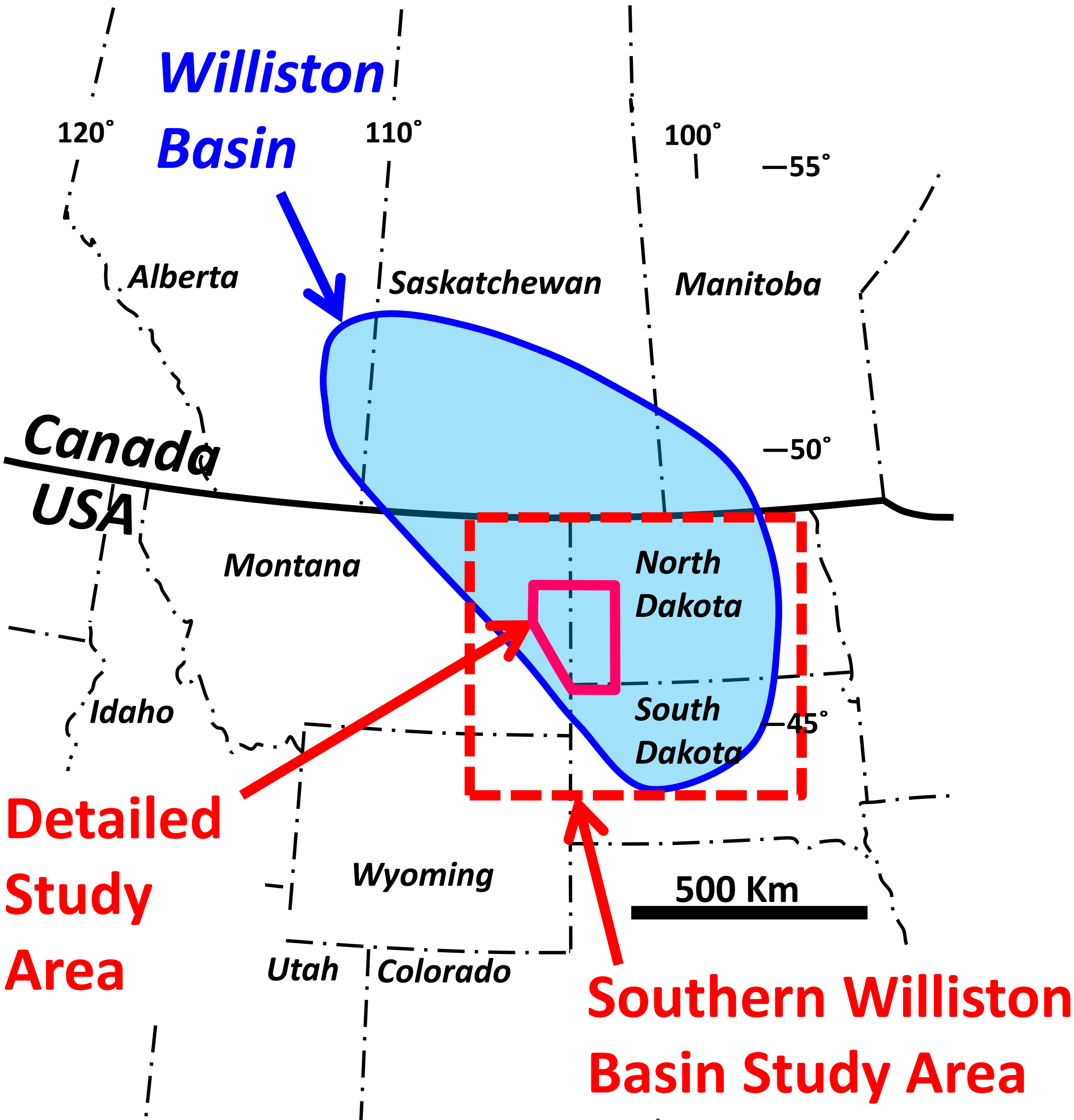
By

David M. Petty



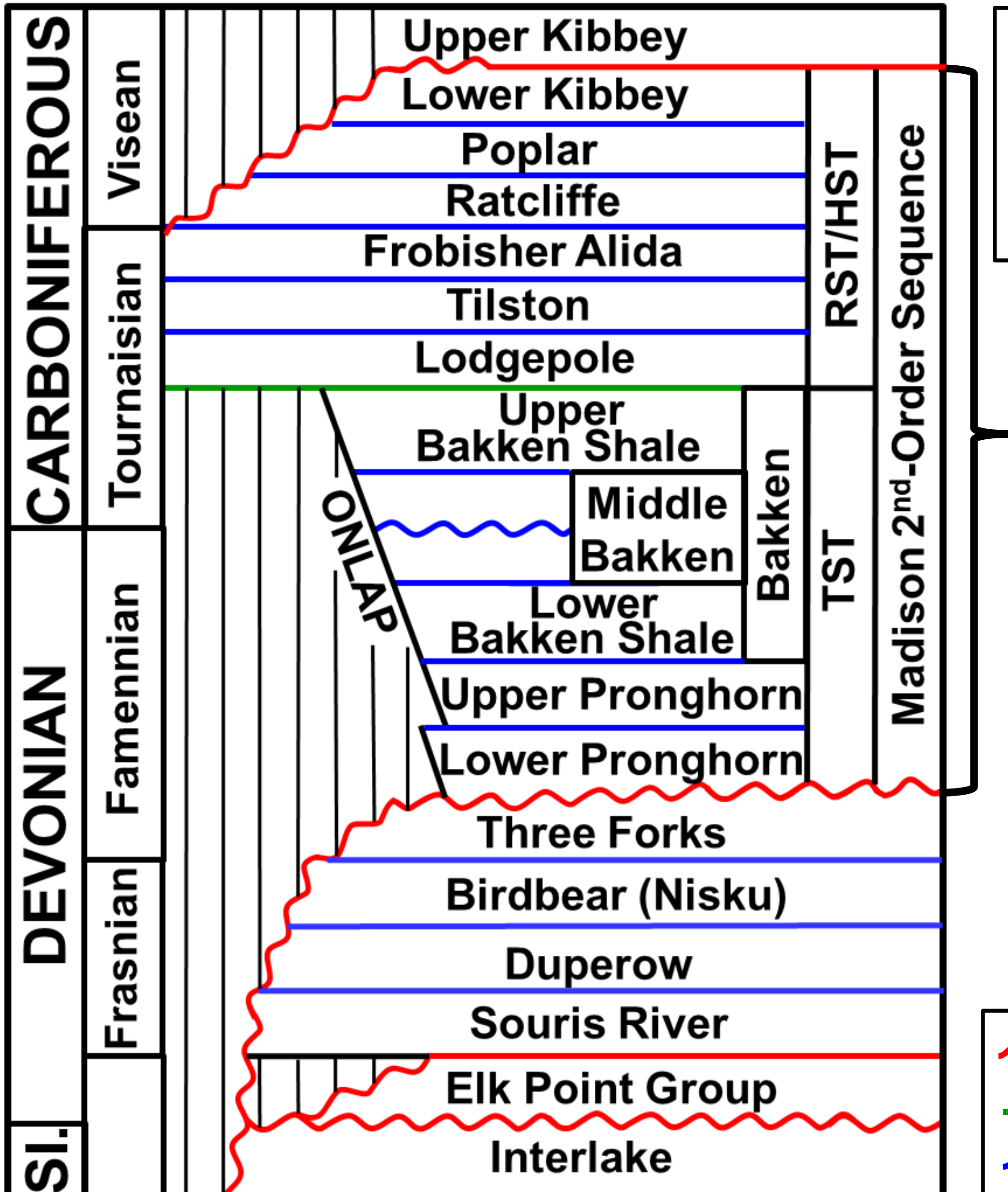


Williston Basin
120°
110°
100°
—55°
Alberta
Saskatchewan
Manitoba
Canada
USA
—50°
Montana
North Dakota
Idaho
South Dakota
—45°
Detailed Study Area
Wyoming
500 Km
Utah
Colorado
Southern Williston Basin Study Area

Introduction

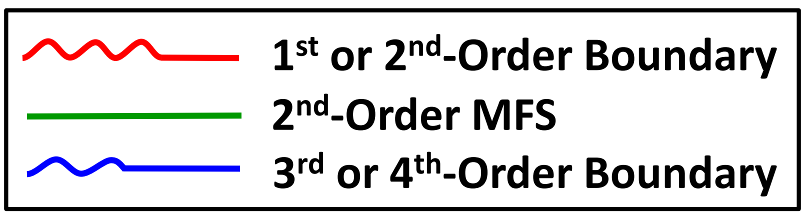
- The "Acadian Discontinuity" is represented by a late-Devonian, angular unconformity (the "Acadian unconformity") that lies on top of the Three Forks Formation in the central portions of the Williston basin, and on older Devonian through Cambrian strata in basin-margin areas (Wheeler, 1963, Boyd, 1997)

Stratigraphic Column
Southwest
Williston Basin Area

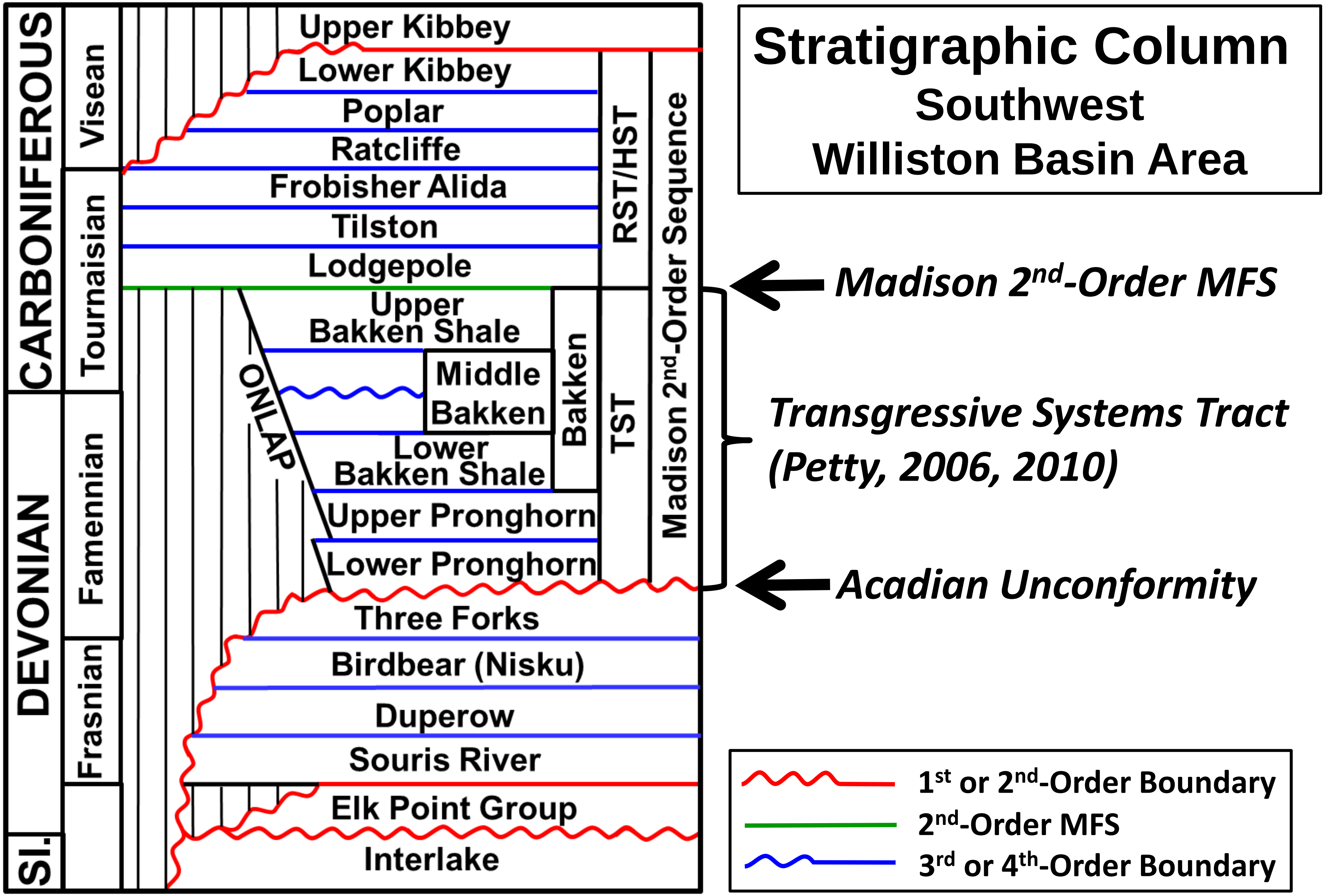


Madison 2nd-Order Sequence (Petty, 2006, 2010)

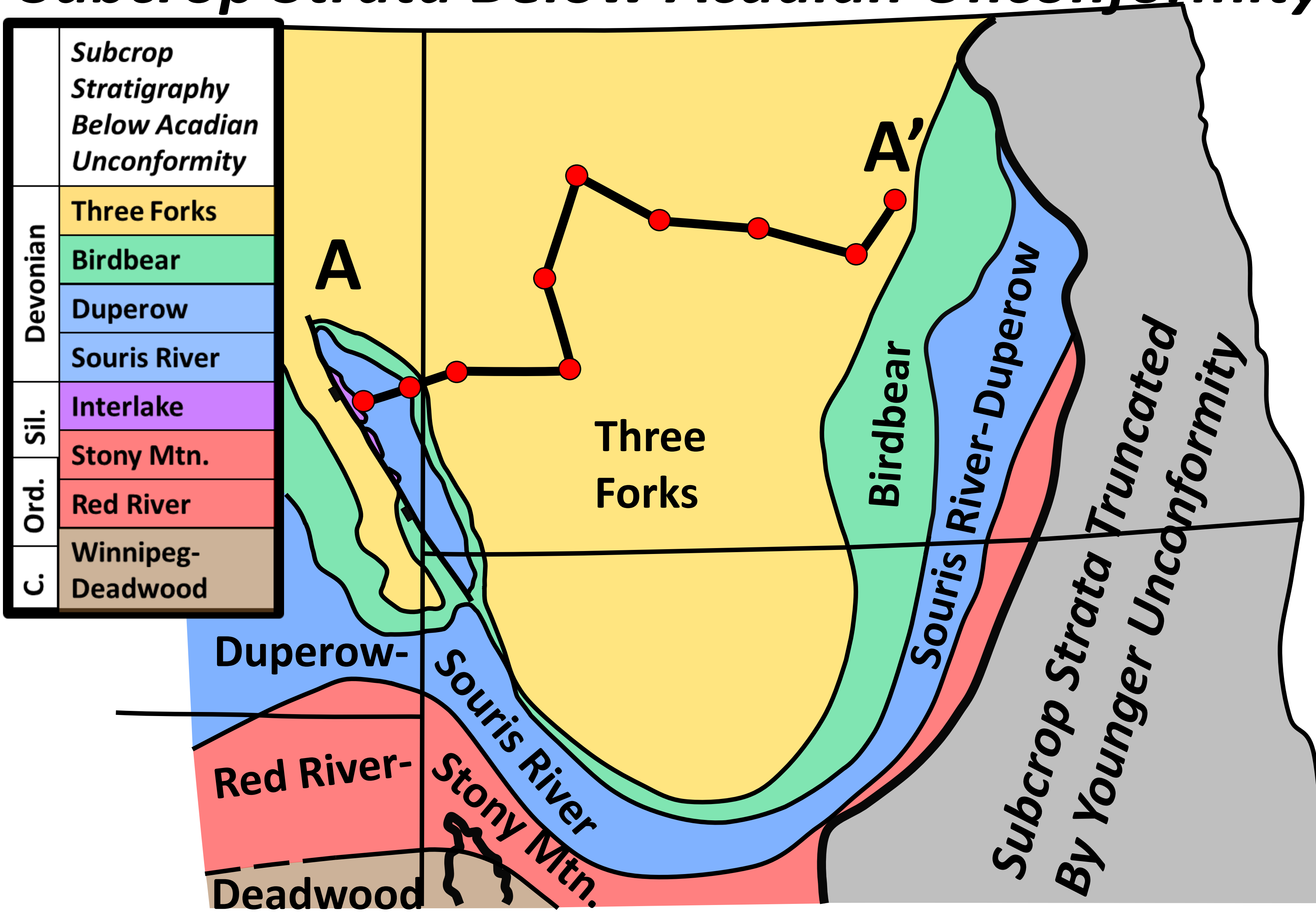
- *Bounded by subaerial unconformities*
- *HST = 20 m.y.*
- *TST = 8 m.y.*

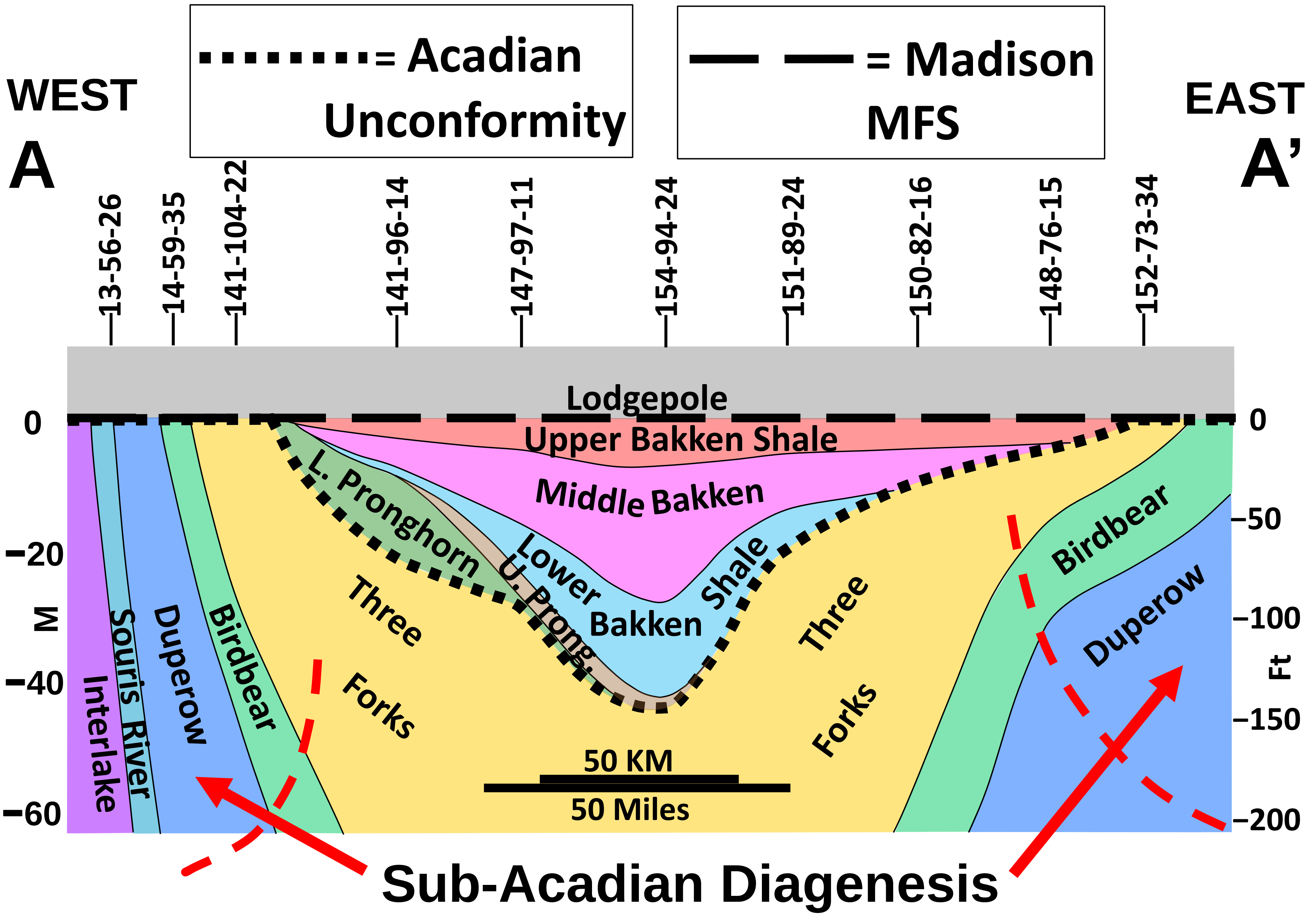


Stratigraphic Column Southwest Williston Basin Area



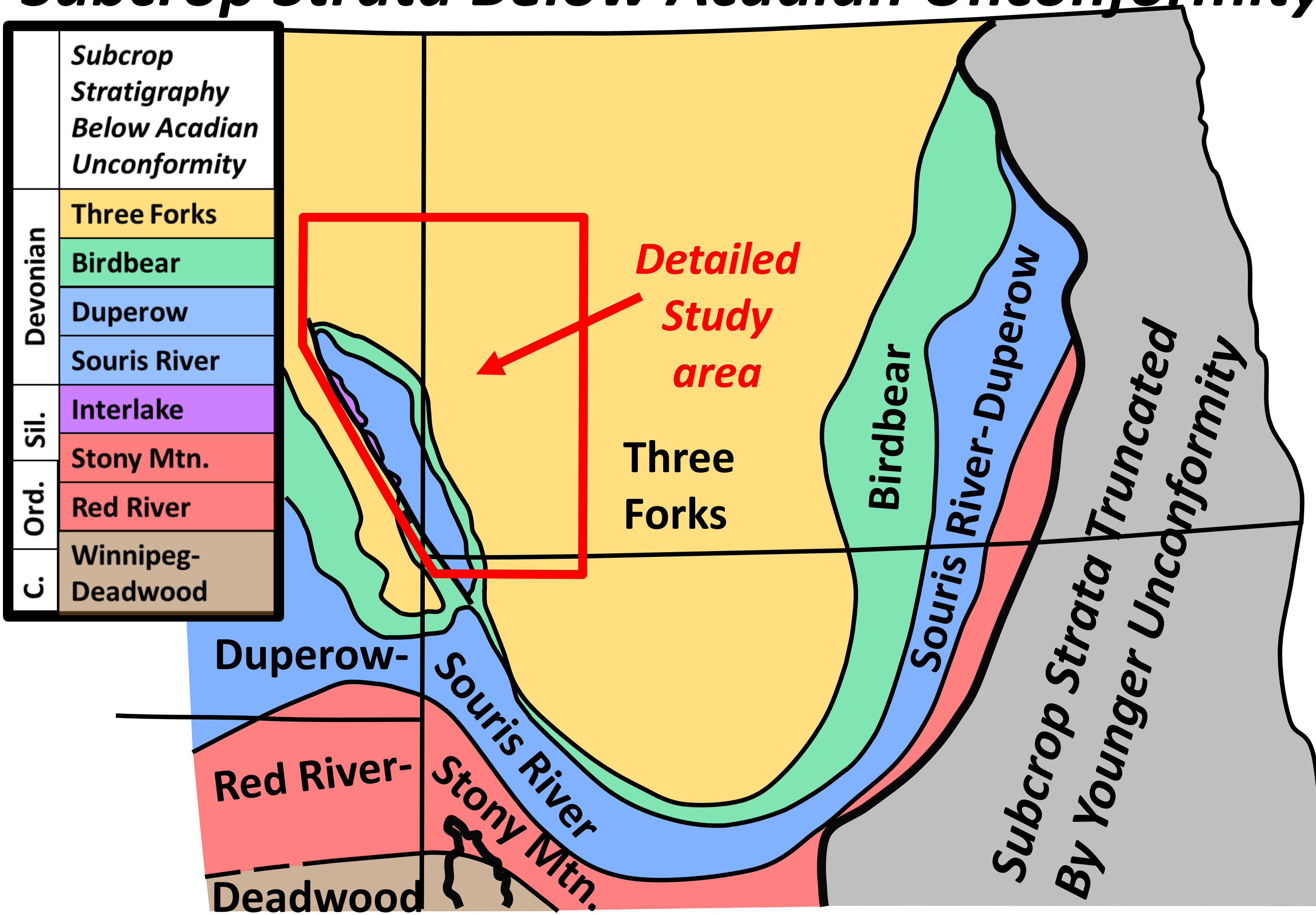
Subcrop Strata Below Acadian Unconformity



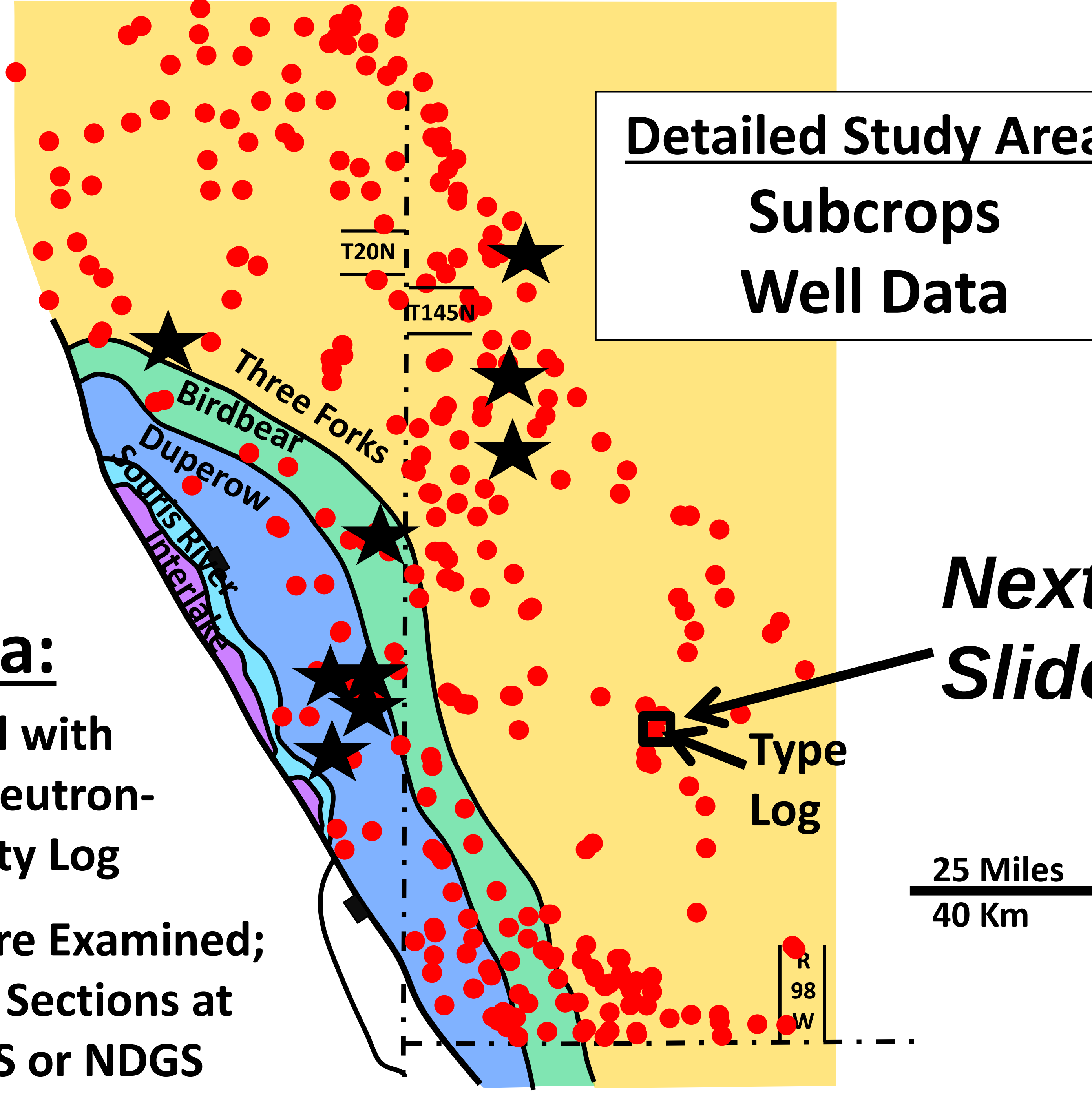


WEST
A
EAST
A'
= Acadian Unconformity
= Madison MFS
13-56-26
14-59-35
141-104-22
141-96-14
147-97-11
154-94-24
151-89-24
150-82-16
148-76-15
152-73-34
Lodgepole
Upper Bakken Shale
Middle Bakken
L. Pronghorn
U. Prong.
Lower Bakken Shale
Three Forks
Three Forks
Interlake
Souris River
Duperow
Birdbear
Birdbear
Duperow
0
-20
-40
-60
M
0
-50
-100
-150
-200
Ft
50 KM
50 Miles
Sub-Acadian Diagenesis

Subcrop Strata Below Acadian Unconformity



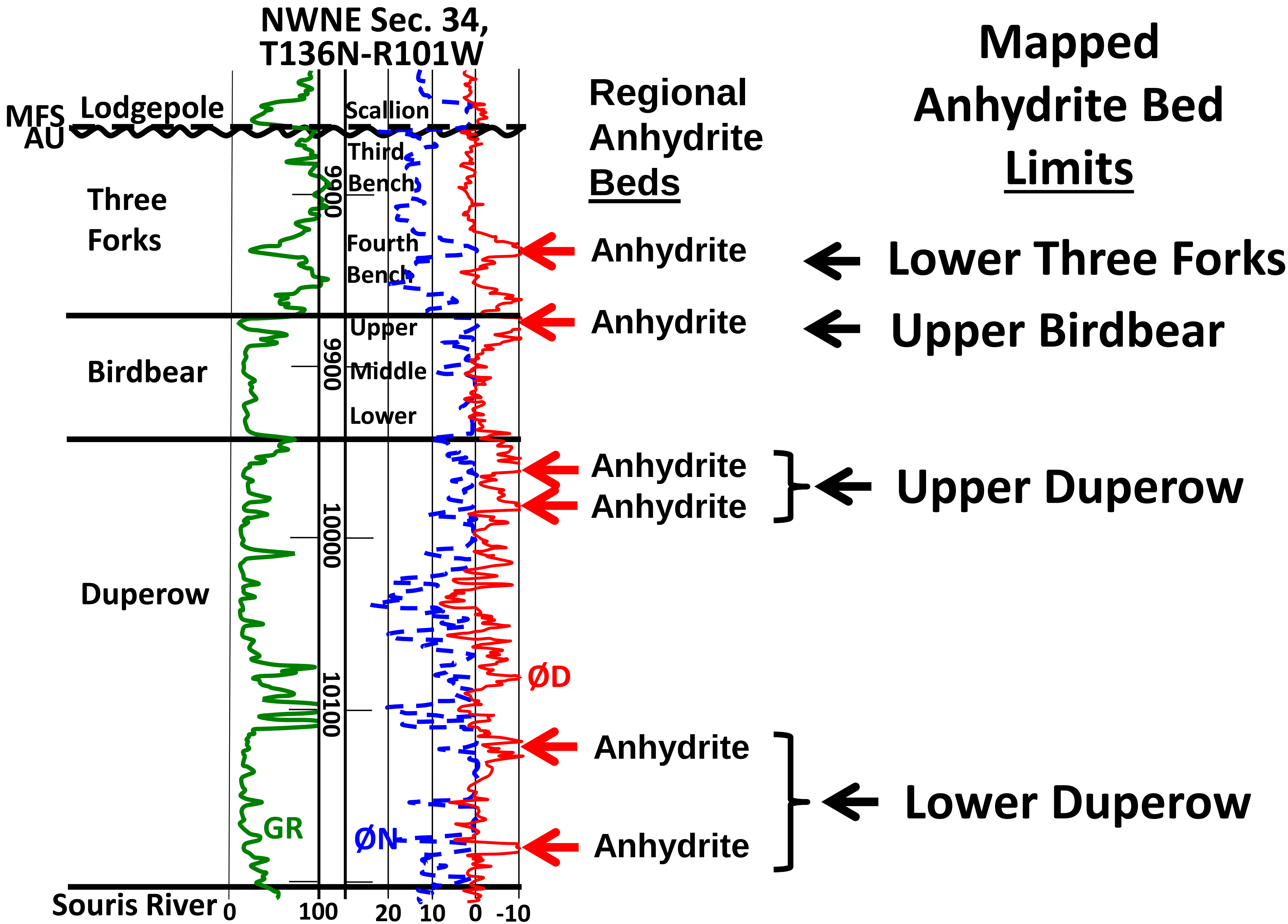
Detailed Study Area:
Subcrops
Well Data



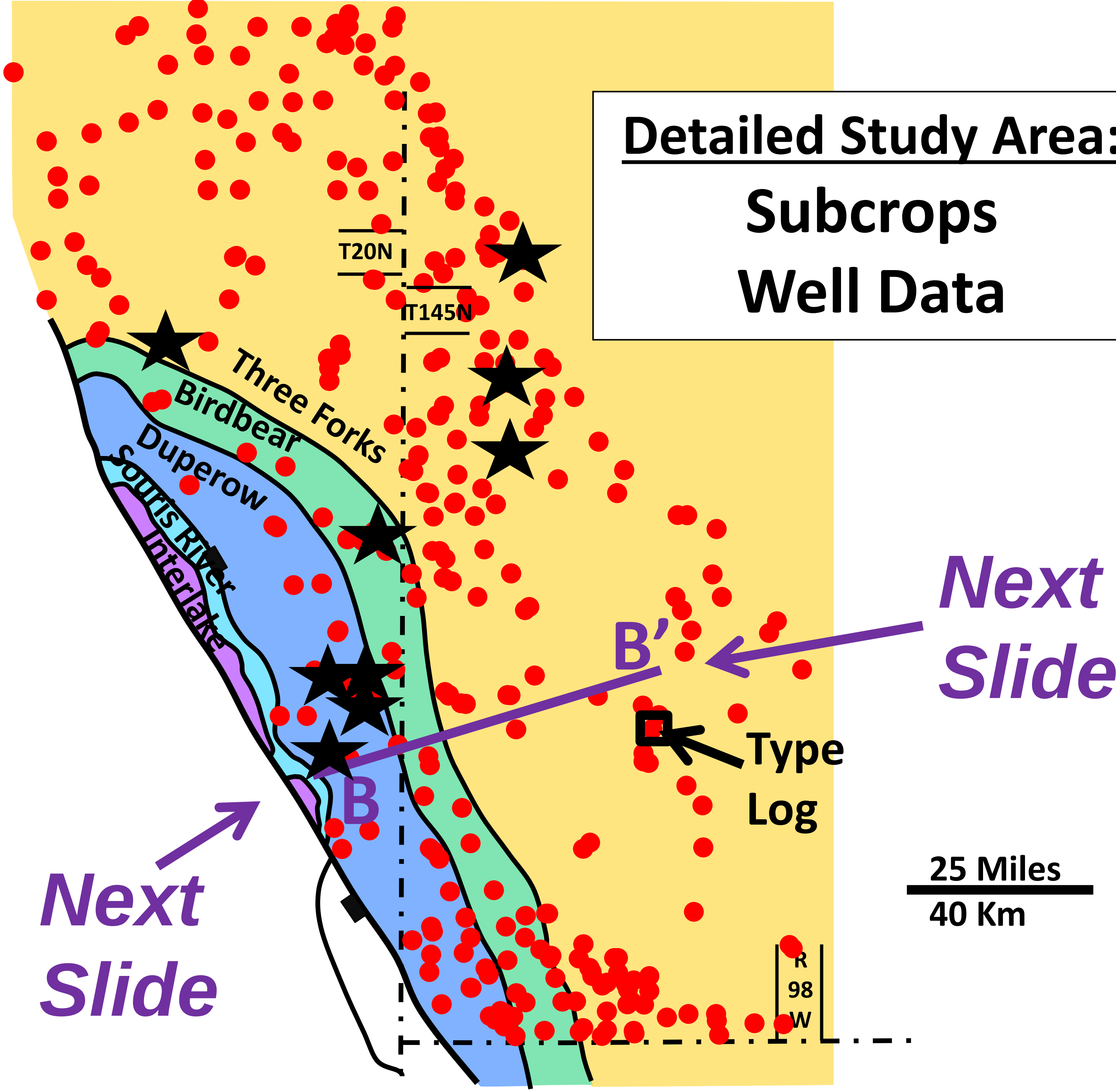
Next Slide

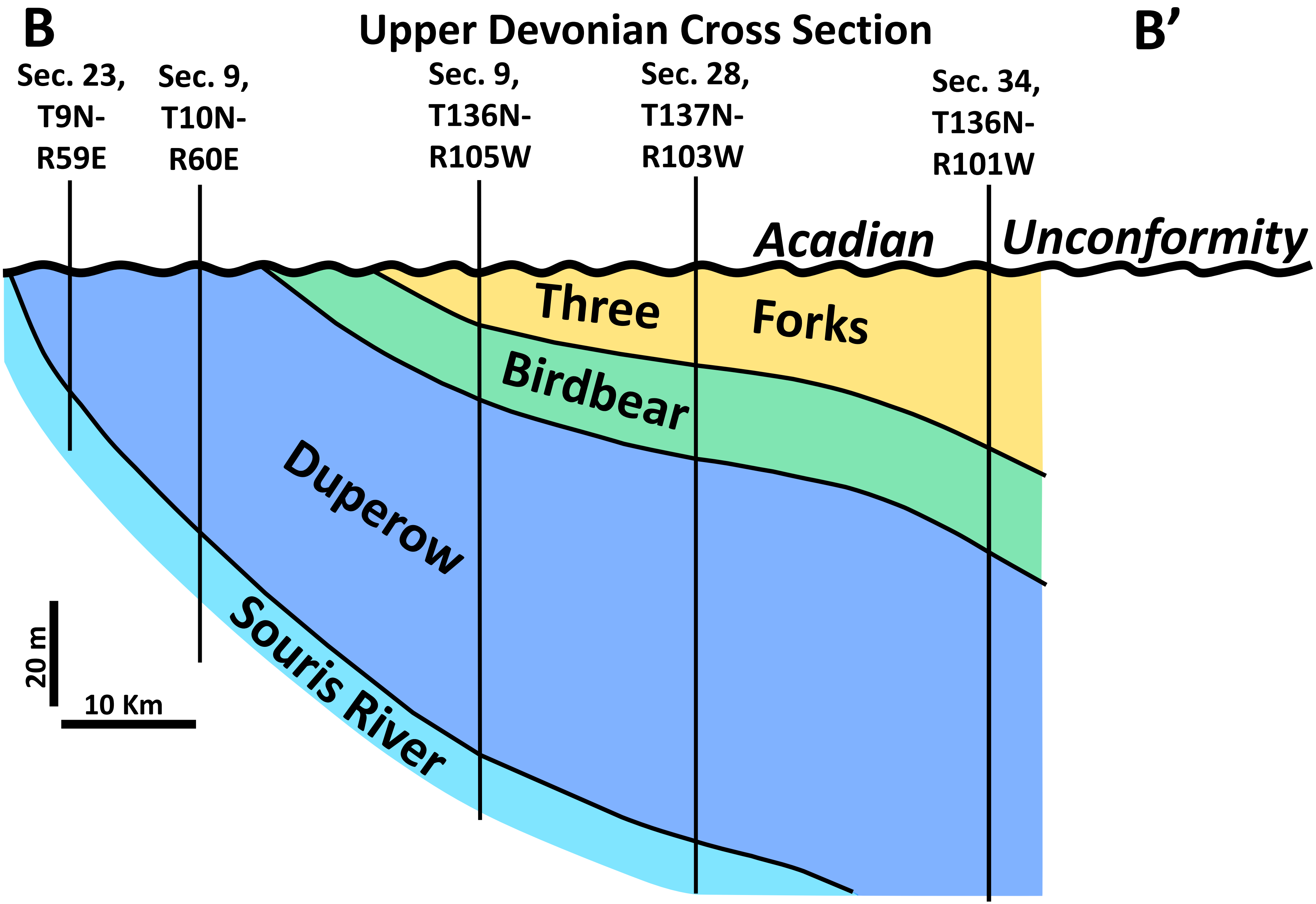
Data:

- ● = Well with GR- Neutron- Density Log
- ★ = Core Examined; Thin Sections at USGS or NDGS


NWNE Sec. 34,
T136N-R101W
MFS
AU
Lodgepole
Scallion
Third
Bench
Three
Forks
Fourth
Bench
Upper
Birdbear
Middle
Lower
Duperow
Souris River
9800
9900
10000
10100
GR
ØN
ØD
0
100
20
10
0
-10
Regional
Anhydrite
Beds
Anhydrite
Anhydrite
Anhydrite
Anhydrite
Anhydrite
Anhydrite
Mapped
Anhydrite Bed
Limits
Lower Three Forks
Upper Birdbear
Upper Duperow
Lower Duperow

Detailed Study Area:
Subcrops
Well Data

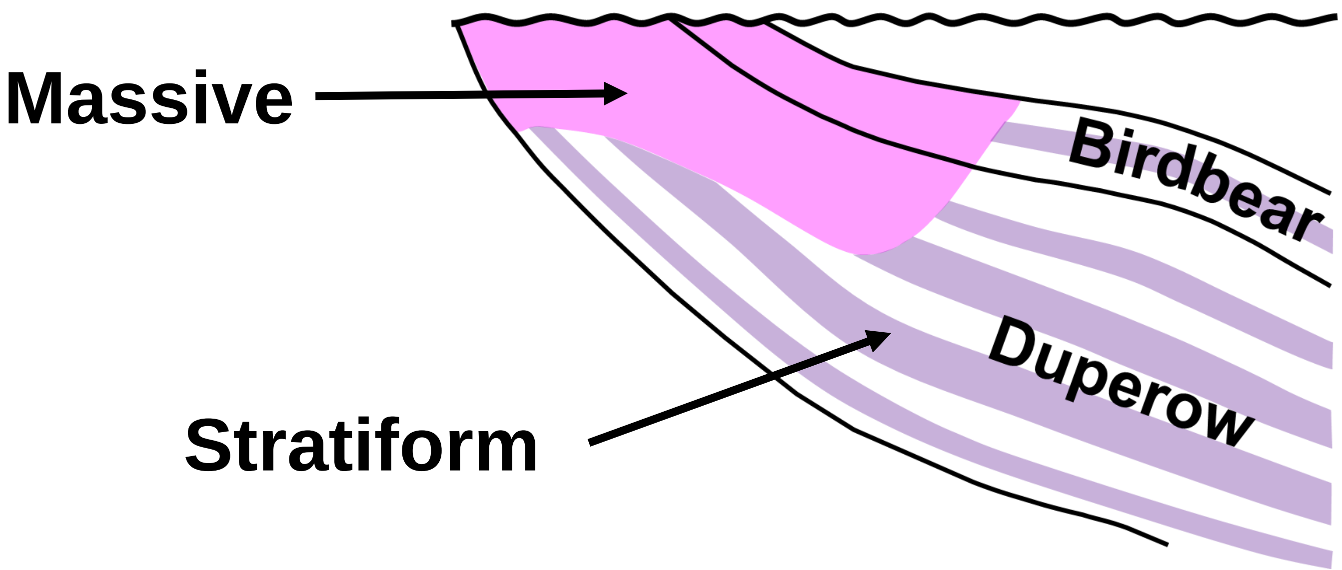



B
Upper Devonian Cross Section
B'
Sec. 23, T9N-R59E
Sec. 9, T10N-R60E
Sec. 9, T136N-R105W
Sec. 28, T137N-R103W
Sec. 34, T136N-R101W
Acadian Unconformity
Three Forks
Birdbear
Duperow
Souris River
20 m
10 Km

Diagenesis

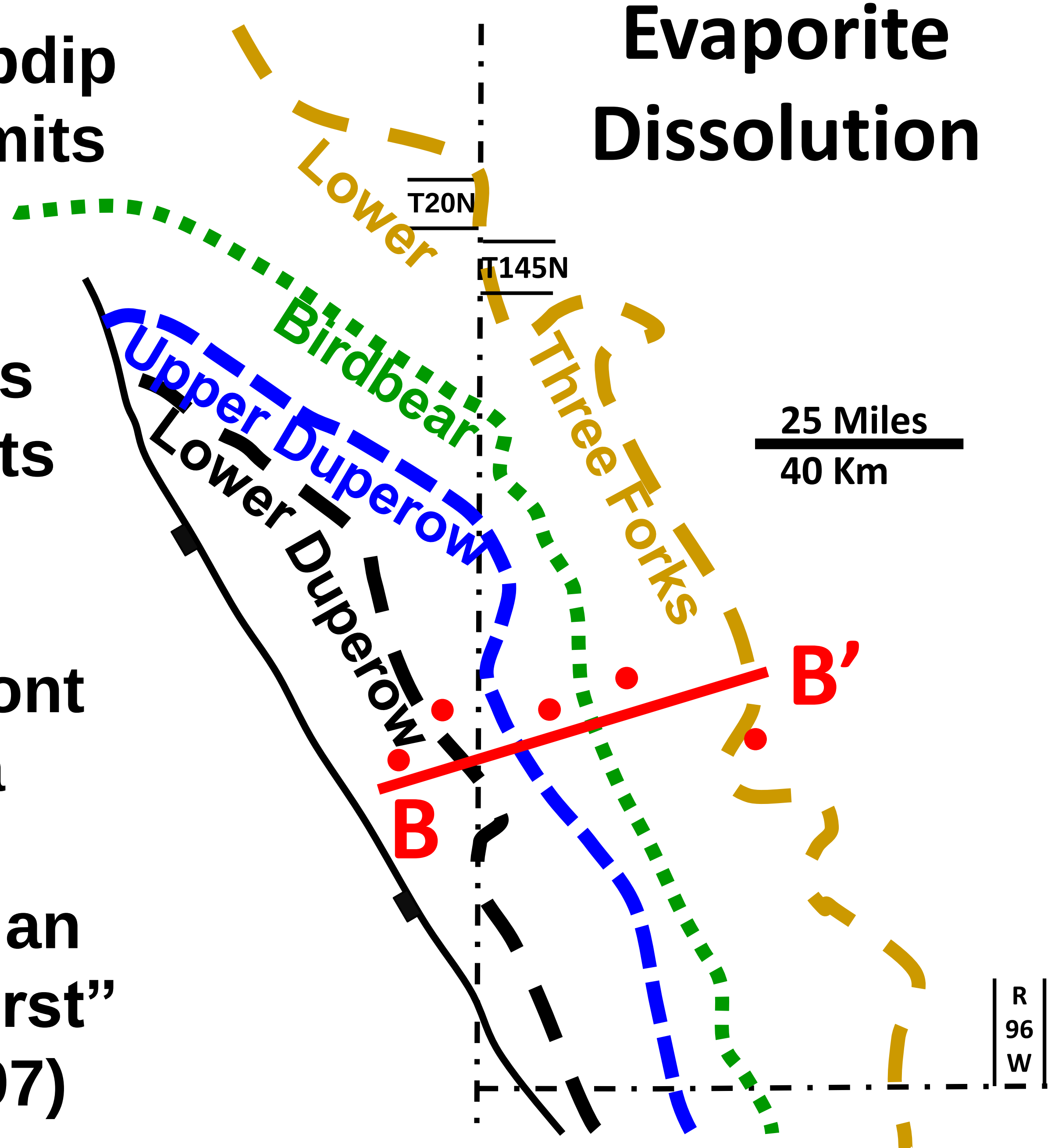
2 Major, Regional and *Mappable* diagenetic features will be discussed:

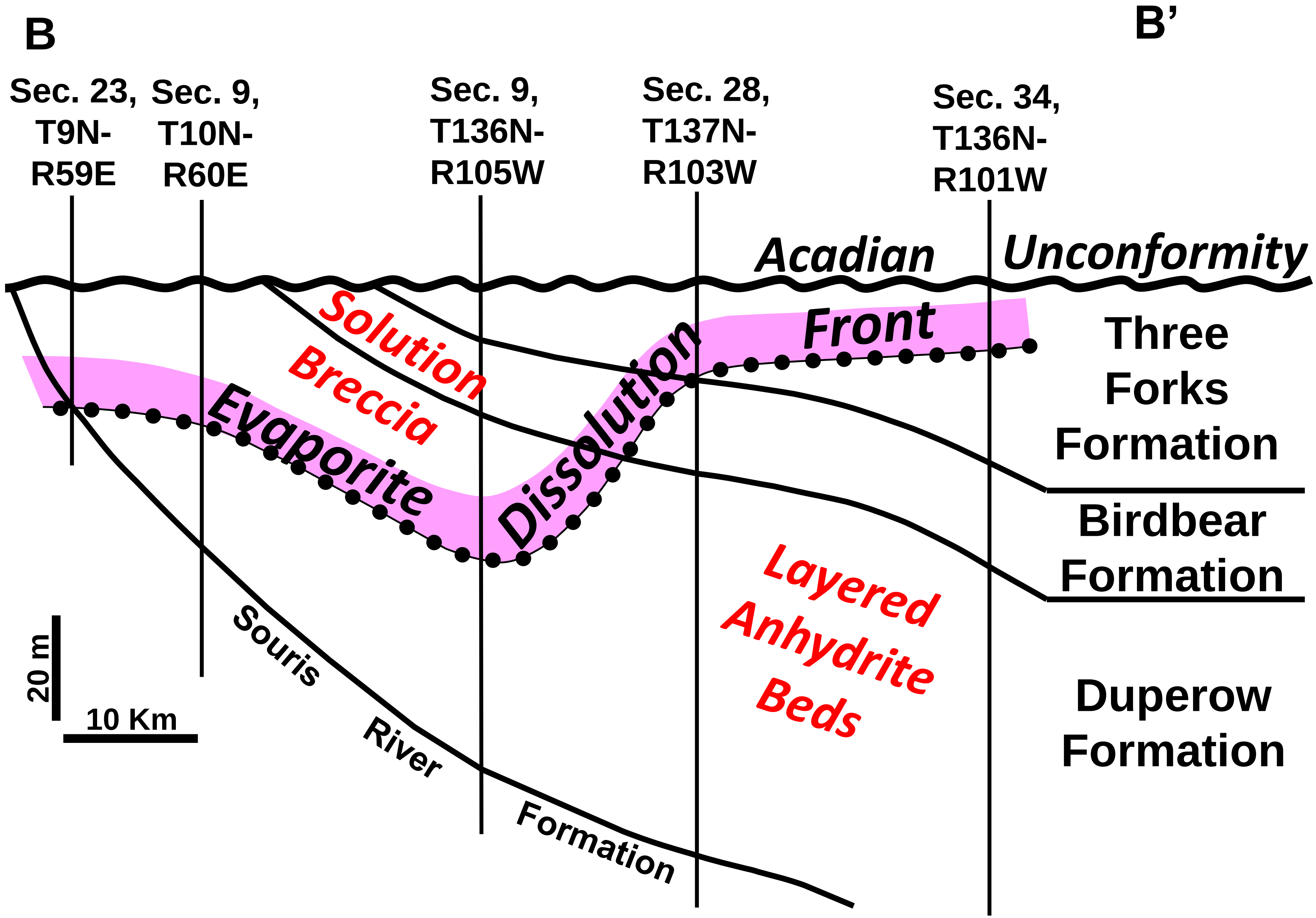
1. **Evaporite dissolution**
2. **Massive dolomitization**
   - **"Massive" = lack of stratiform geometry**



- Map shows updip dissolution limits for regionally continuous anhydrite beds
- Evaporite limits define a sub-unconformity dissolution front
- This defines a type of karst referred to as an "Evaporite Karst" (Johnson, 1997)
- B-B' next slide

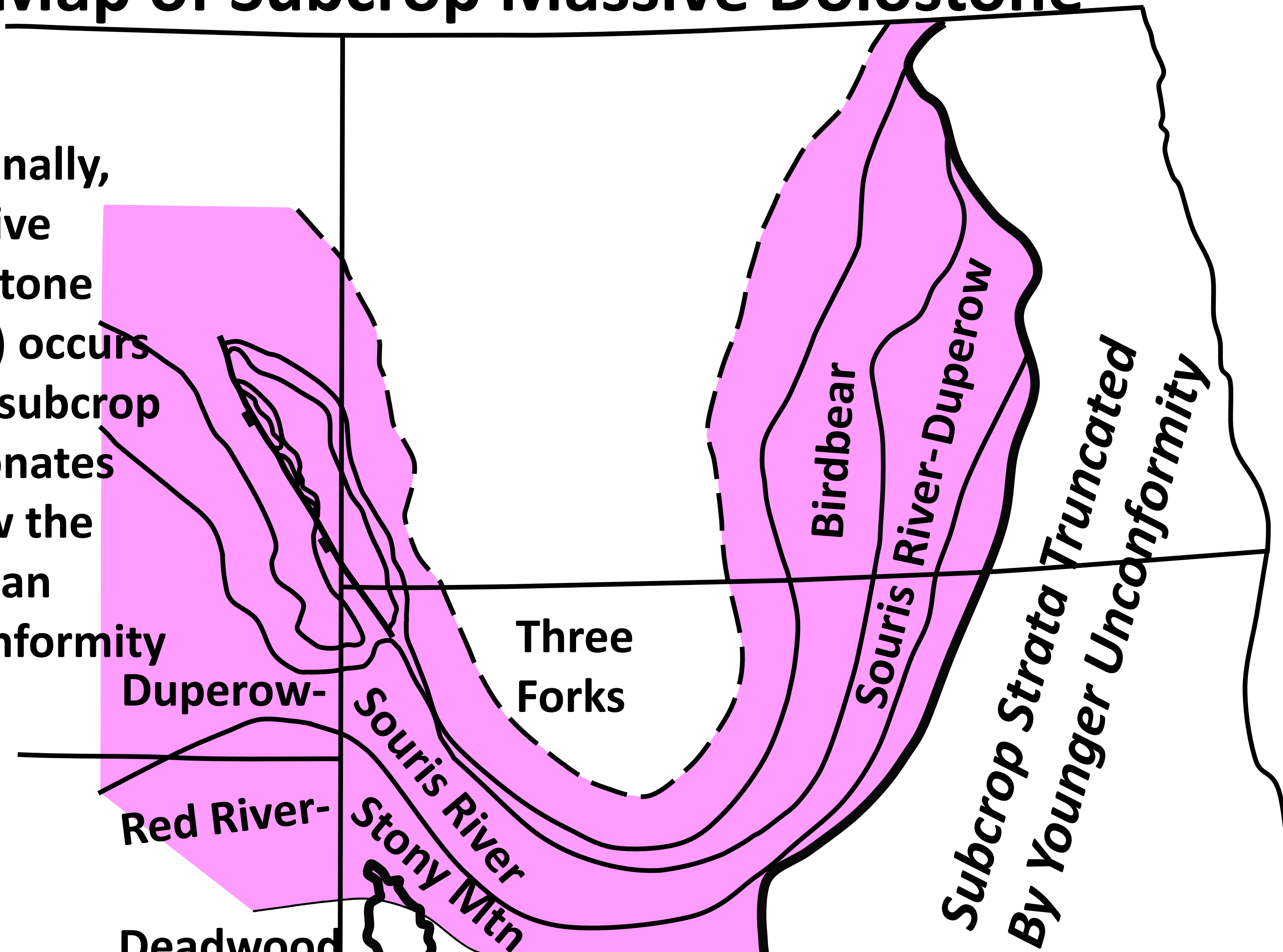
Evaporite Dissolution




B
B’
Sec. 23, T9N-R59E
Sec. 9, T10N-R60E
Sec. 9, T136N-R105W
Sec. 28, T137N-R103W
Sec. 34, T136N-R101W
Acadian Unconformity
Solution Breccia
Evaporite Dissolution Front
Three Forks Formation
Birdbear Formation
Duperow Formation
Layered Anhydrite Beds
Souris River Formation
20 m
10 Km

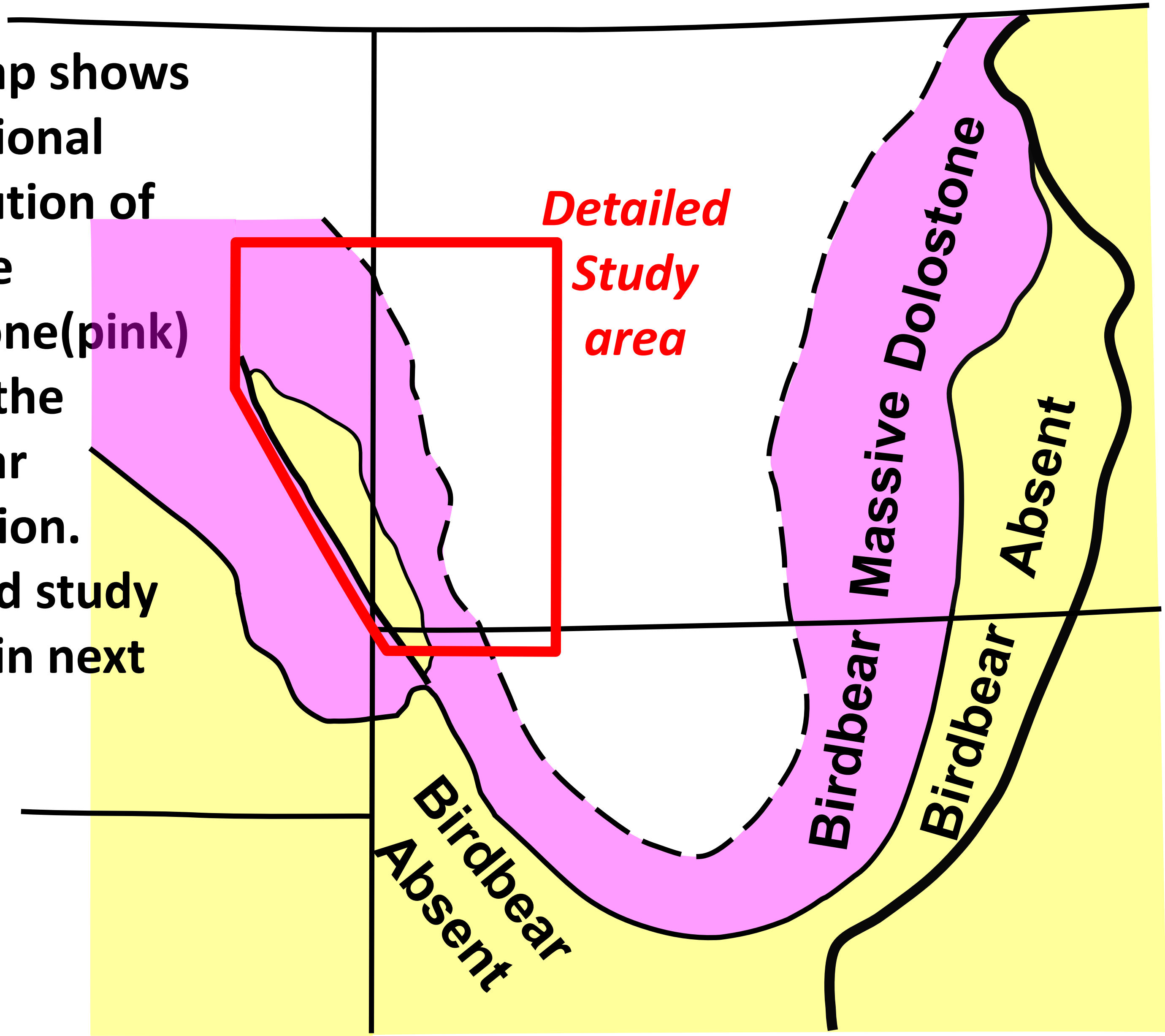
Map of Subcrop Massive Dolostone

Regionally, massive dolostone (pink) occurs in all subcrop carbonates below the Acadian unconformity



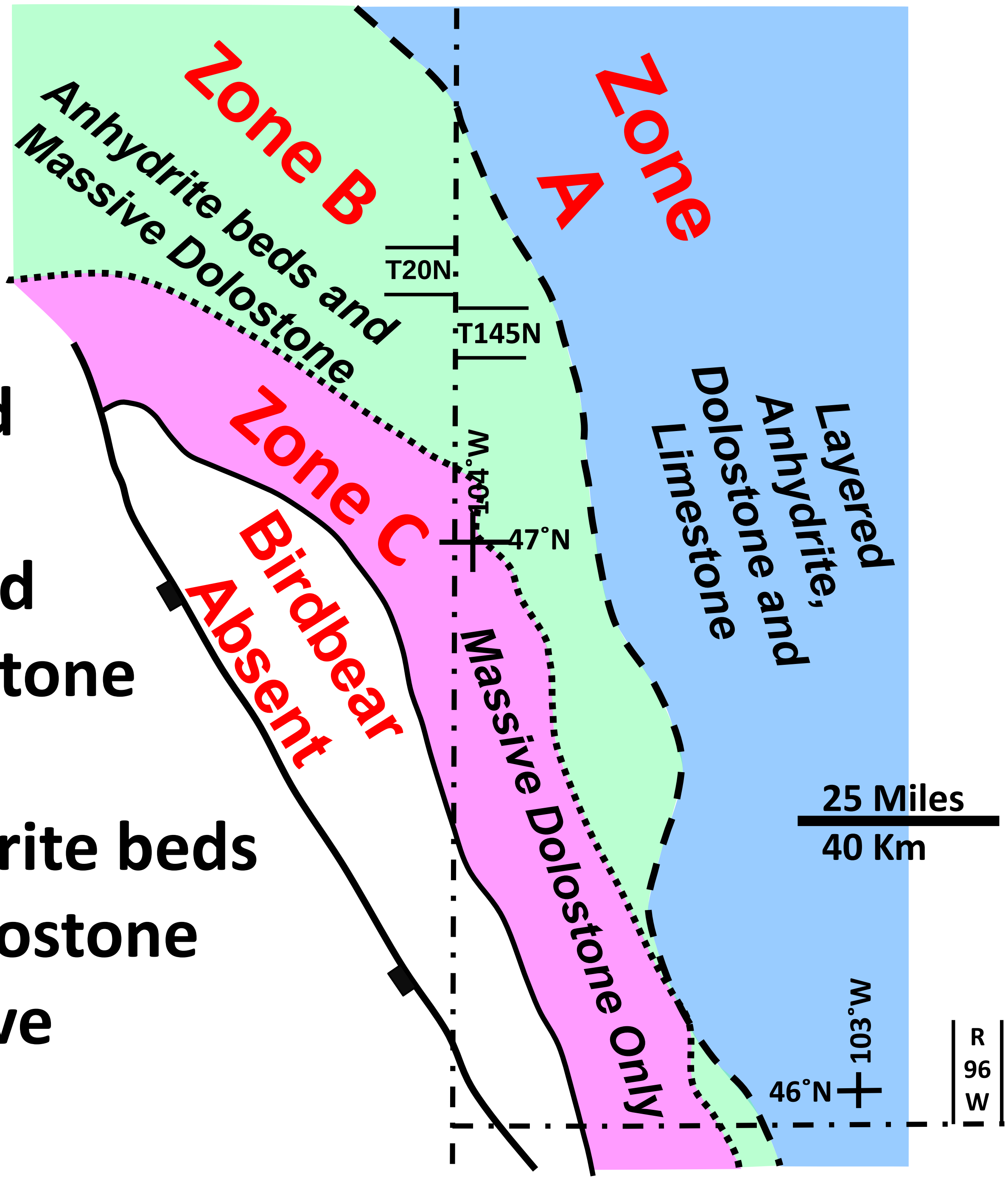
Birdbear Massive Dolostone Distribution

This map shows the regional distribution of massive dolostone(pink) within the Birdbear Formation. Detailed study area is in next slide.

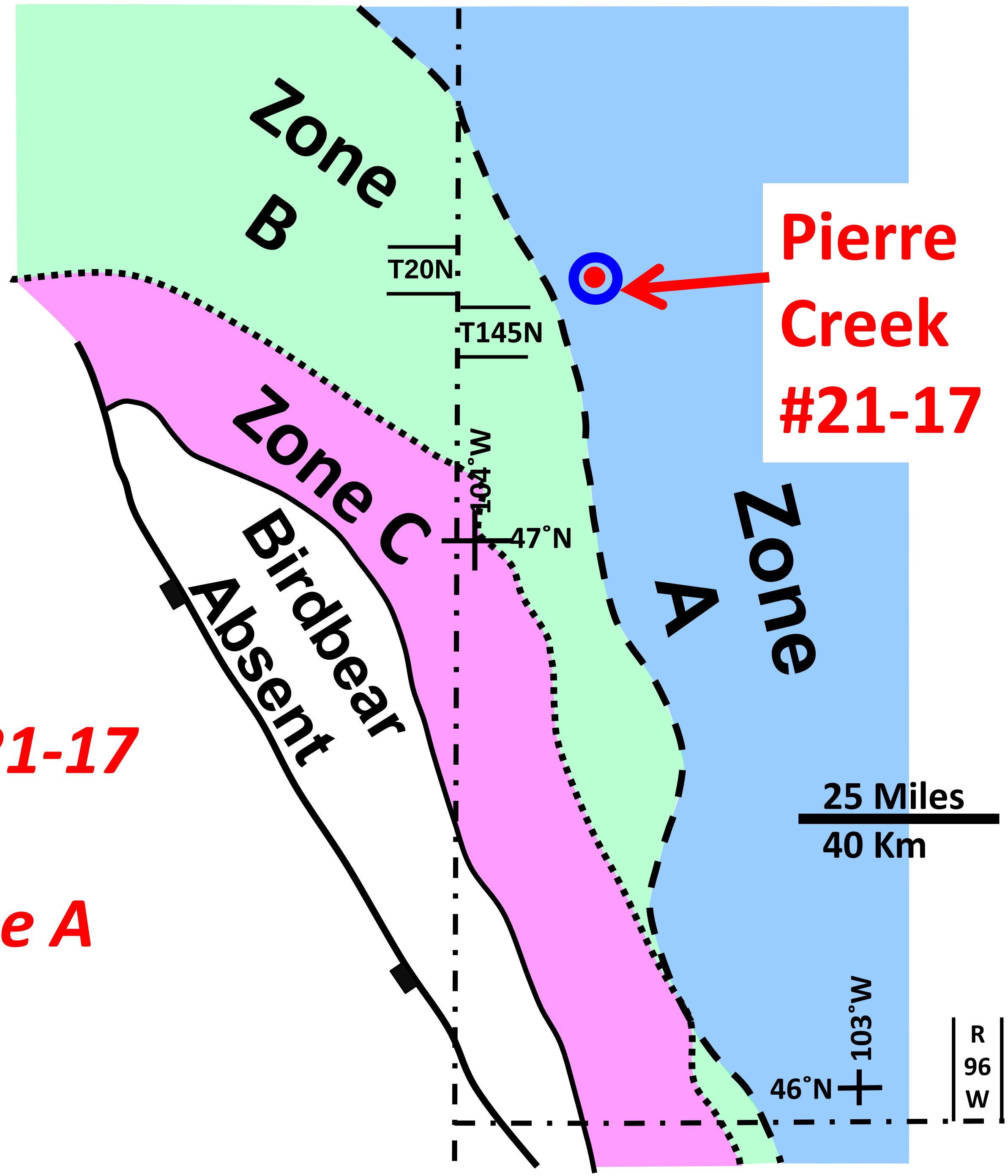


Birdbear Diagenetic Zones

- Lithology-based
- Mappable
- Zone A = layered anhydrite, dolostone and limestone
- Zone B = anhydrite beds and massive dolostone
- Zone C = Massive dolostone only



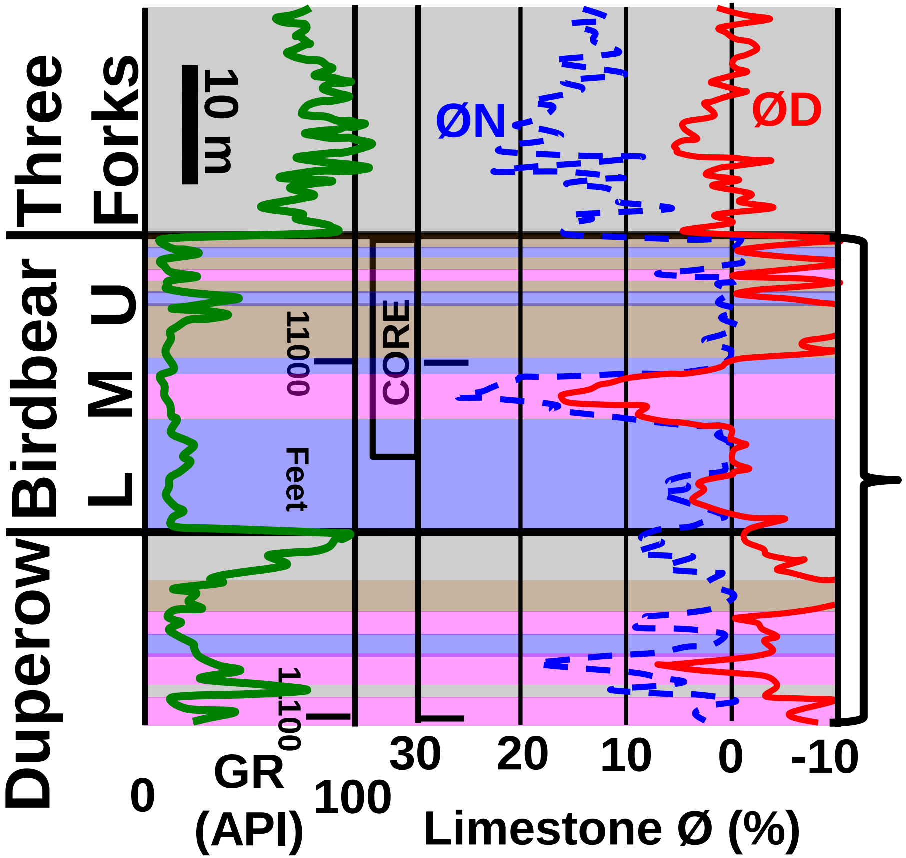
Birdbear Diagenetic Zones



Zone A

Pierre Creek #21-17 illustrates Diagenetic Zone A

Pierre Creek #21-17: Sec. 17, T146N-R102W



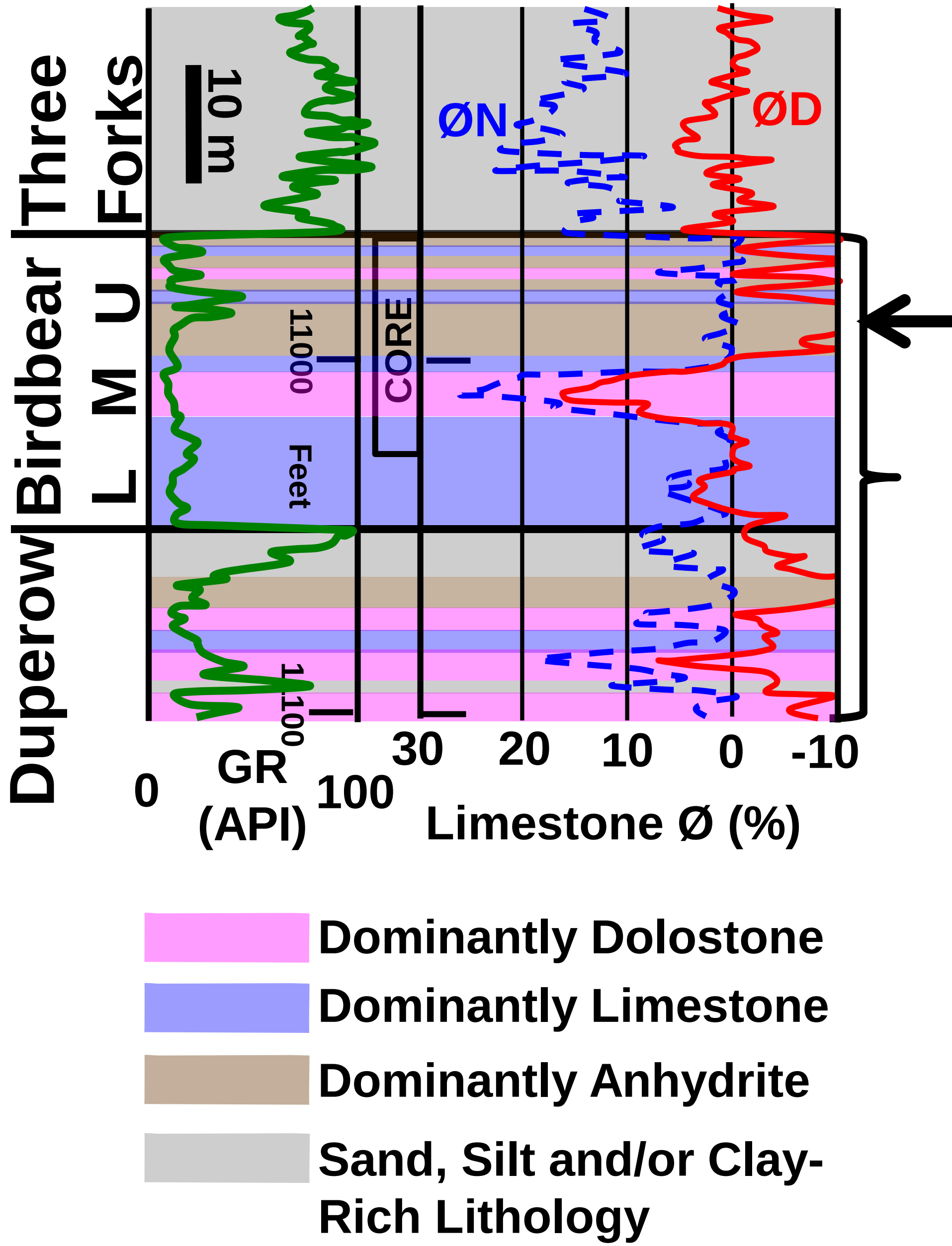
Diagenetic Zone A

Layered limestone, dolostone and anhydrite = downdip area unaffected or marginally affected by sub-unconformity diagenesis

- Dominantly Dolostone
- Dominantly Limestone
- Dominantly Anhydrite
- Sand, Silt and/or Clay-Rich Lithology

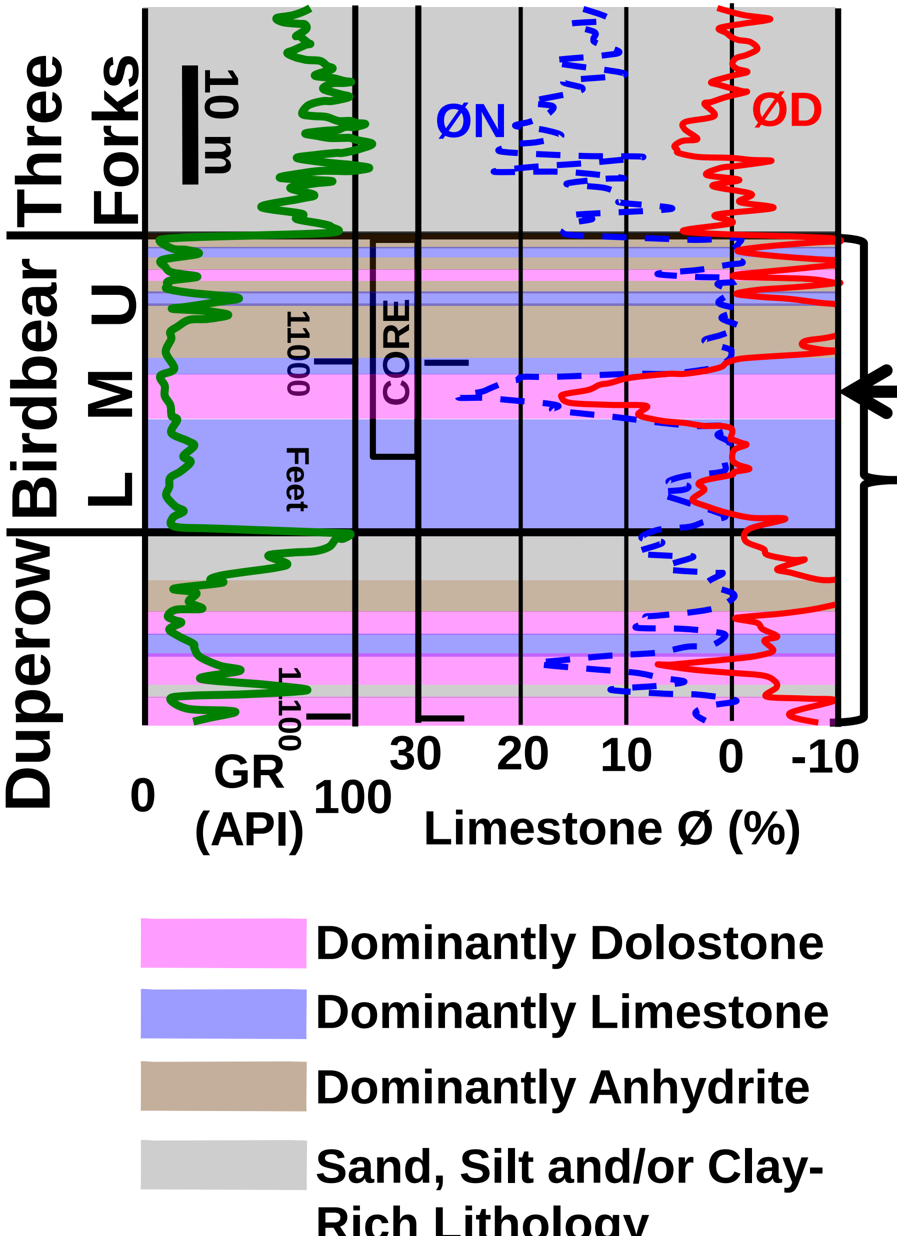
Basic Lithology from GR-Neutron-Density logs tied to core data

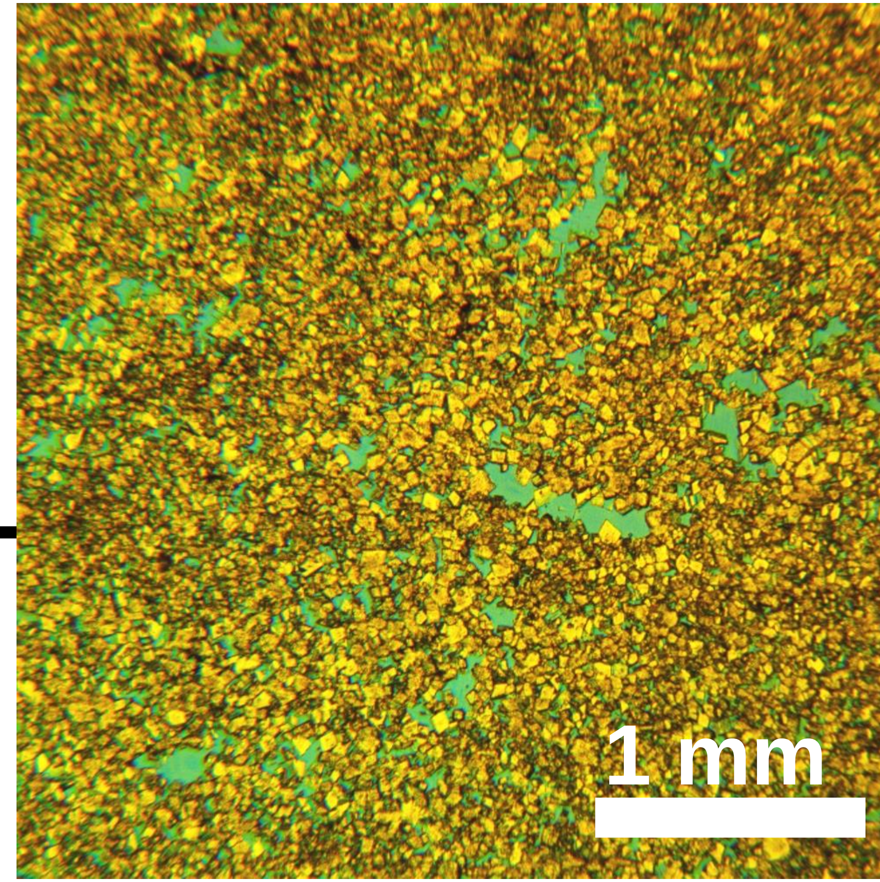
Pierre Creek #21-17:
Sec. 17, T146N-R102W



Birdbear Anhydrite:

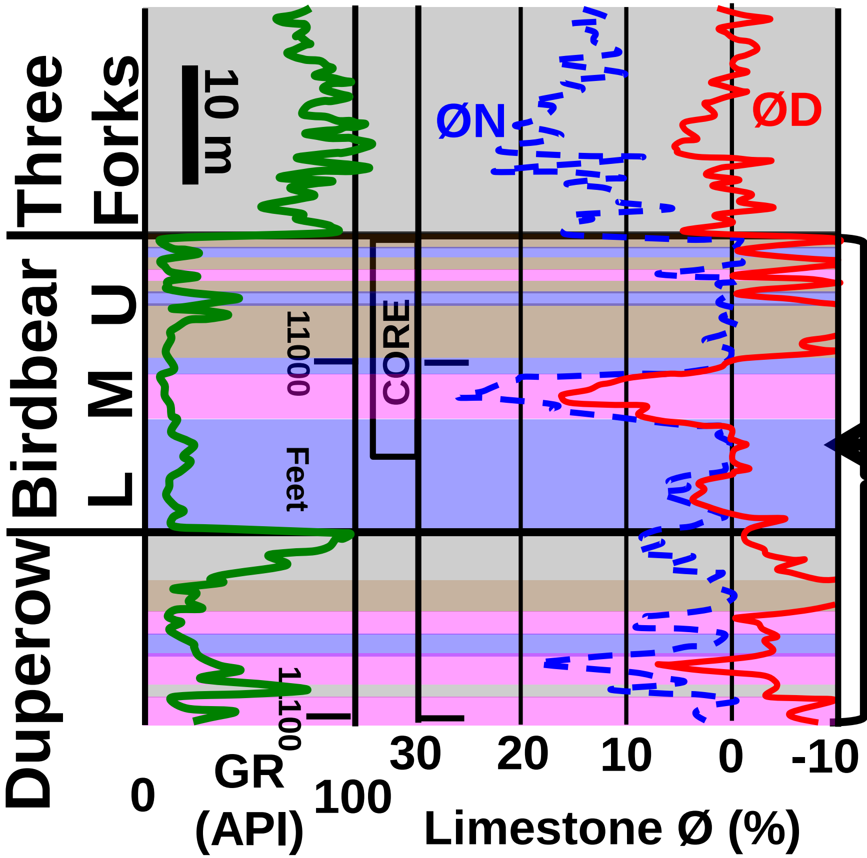
Pierre Creek #21-17:
Sec. 17, T146N-R102W





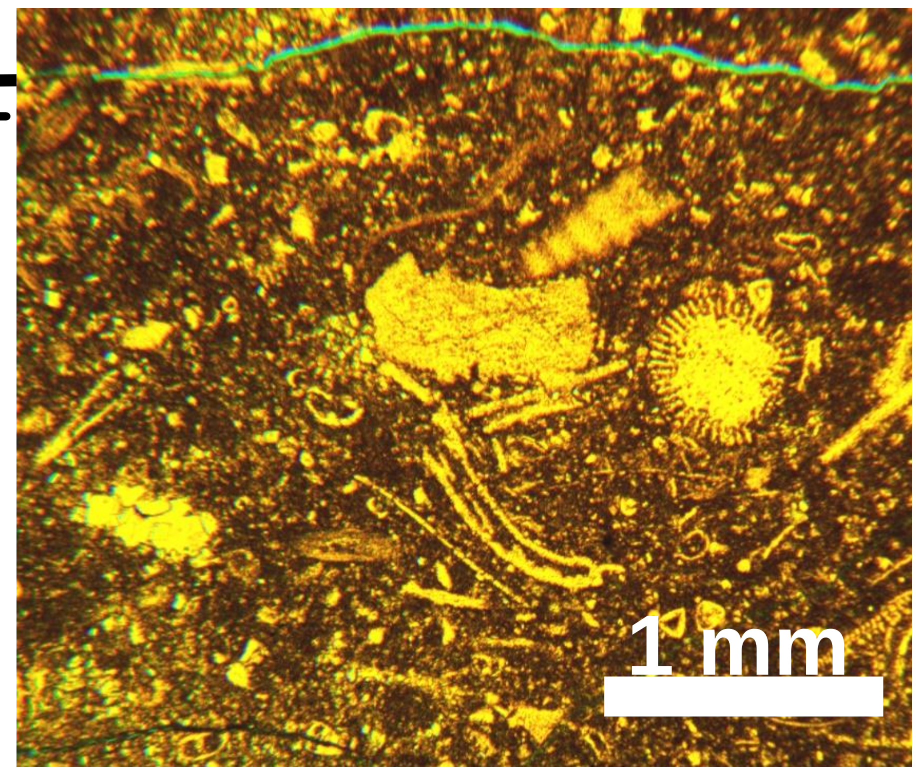
11,007.5’ core depth
Dolomitic Skeletal Mudstone
Average crystal size = 30 µ
Ø = 20; Ka = 71 md

Pierre Creek #21-17:
Sec. 17, T146N-R102W



Dominantly Dolostone
Dominantly Limestone
Dominantly Anhydrite
Sand, Silt and/or Clay-Rich Lithology

11,019’ core depth
Limestone
Skeletal wackestone

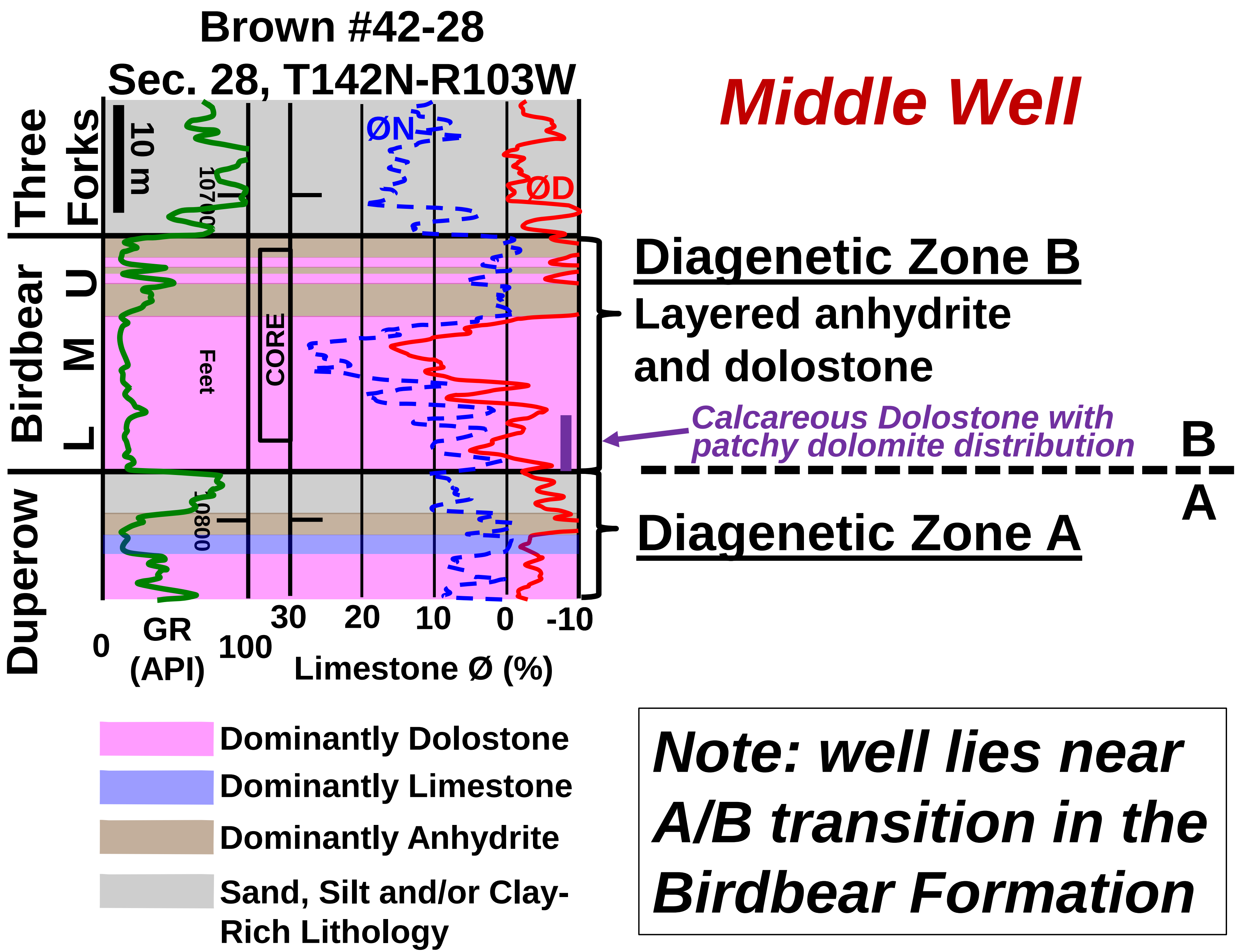


Birdbear Diagenetic Zones

Brown #42-28 illustrates Diagenetic Zone B

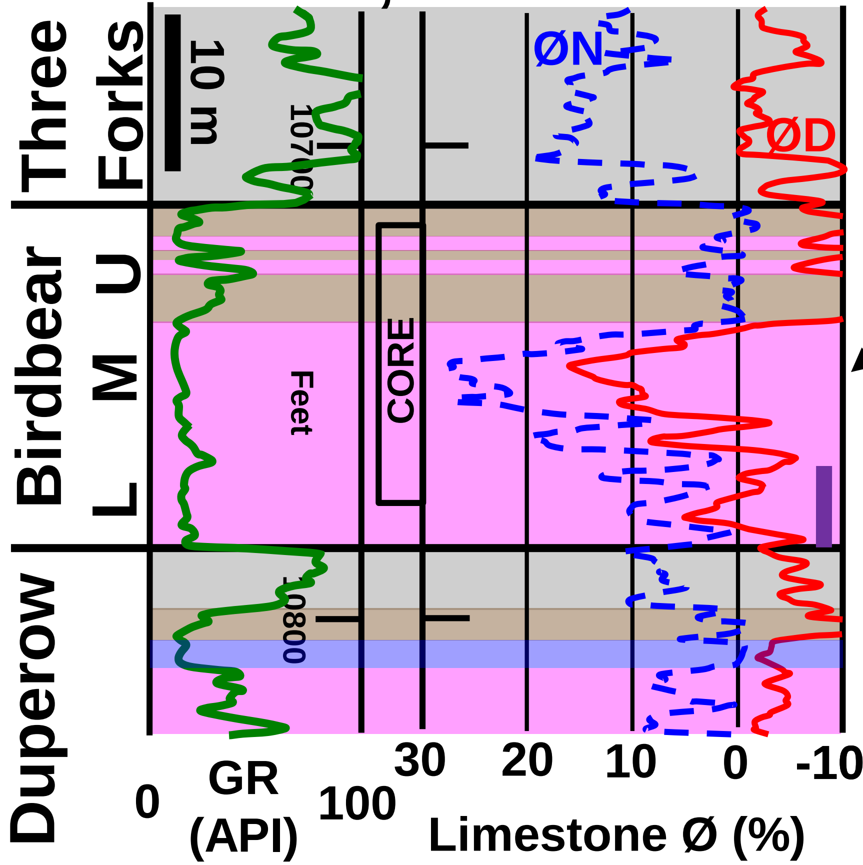
***Note:* well is on downdip edge of Zone B**

Middle Well

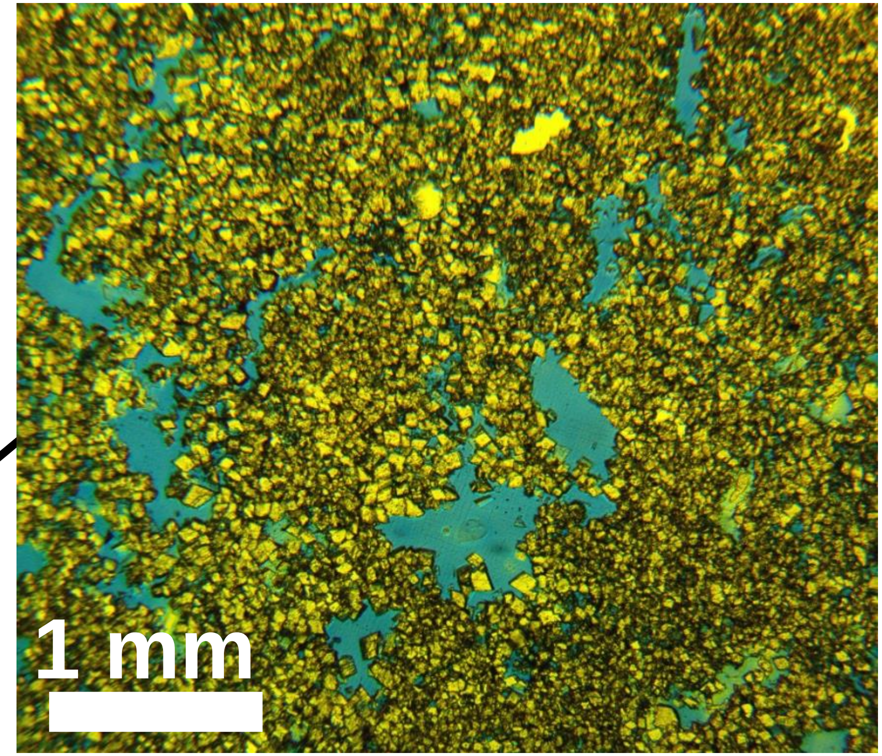


Note: well lies near A/B transition in the Birdbear Formation

Brown #42-28
Sec. 28, T142N-R103W

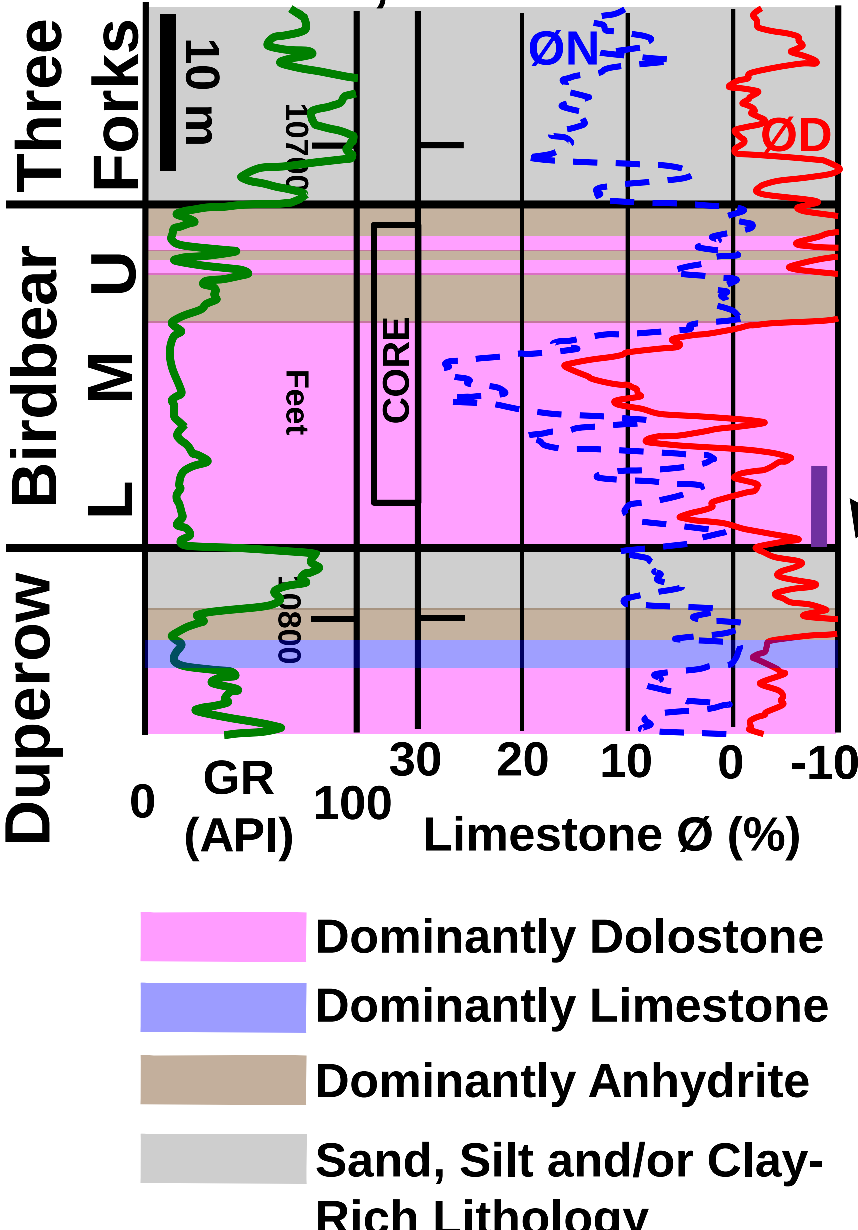


Dominantly Dolostone
Dominantly Limestone
Dominantly Anhydrite
Sand, Silt and/or Clay-Rich Lithology



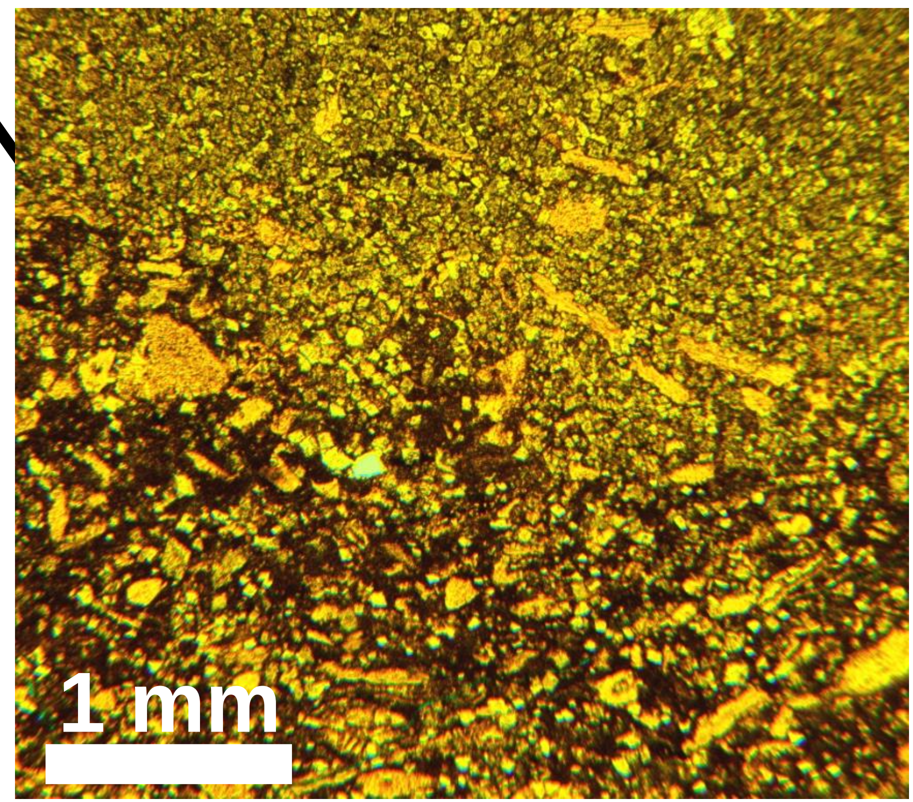
10,730' core depth
Dolomitic
Mudstone/wackestone
Average crystal size = 50 µ
Ø = 22; Ka = 261 md

Brown #42-28
Sec. 28, T142N-R103W



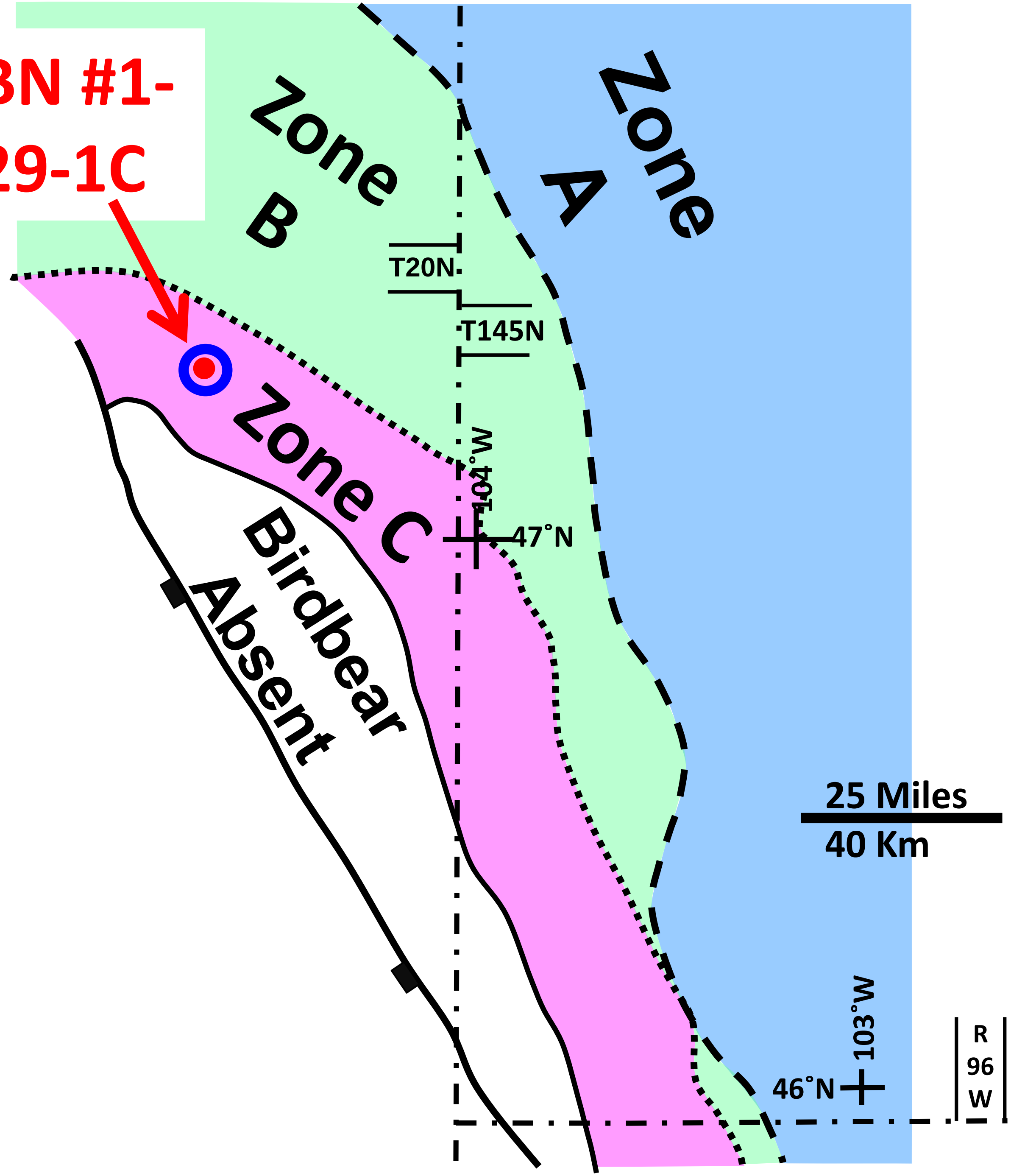
Calcareous Dolostone at Zone A/B Transition; Note "Patchy" Dolomite Distribution

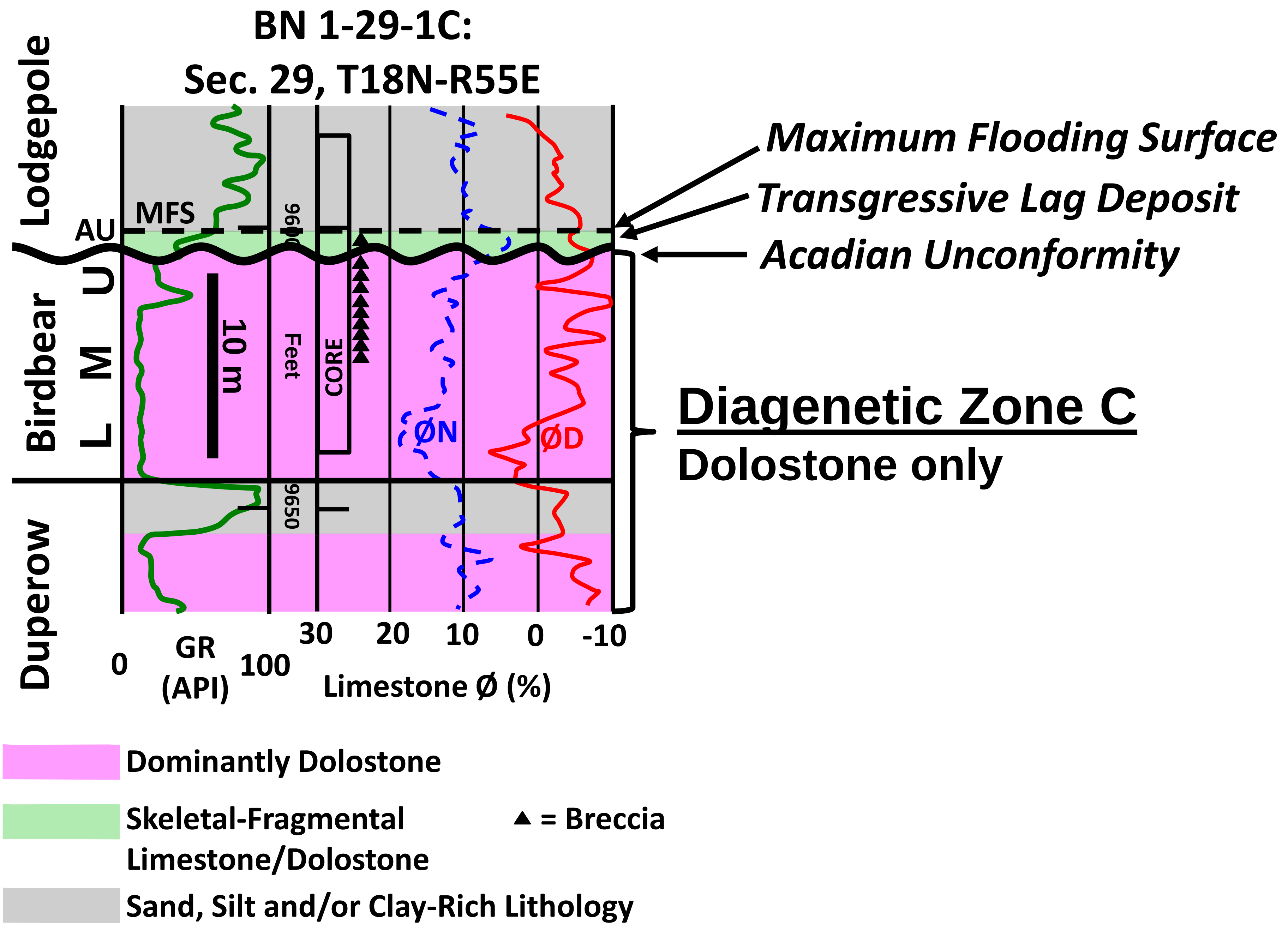
10,752' core depth
Average crystal size = 25 μ



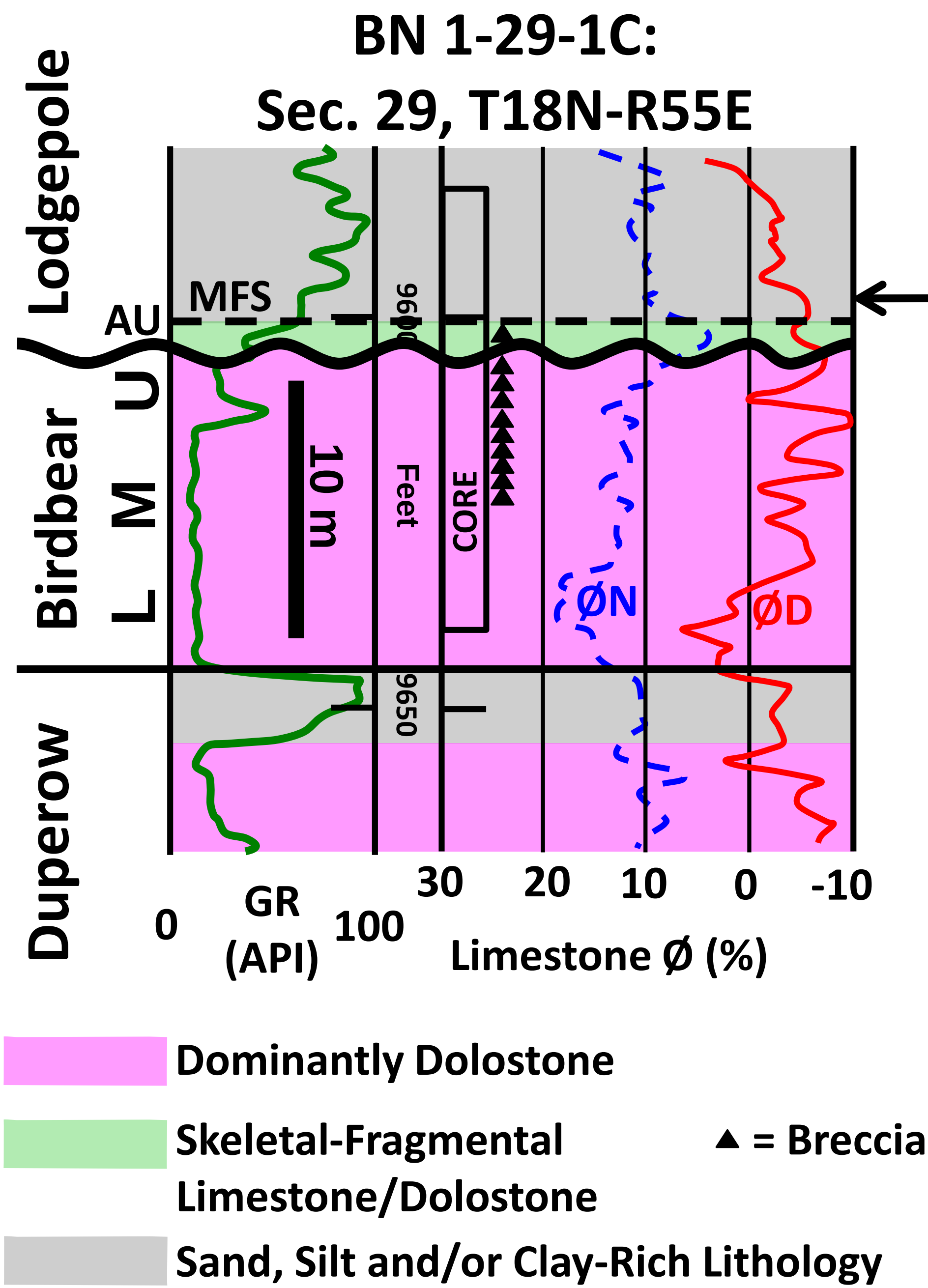
Birdbear Diagenetic Zones

BN #1-29-1C illustrates Diagenetic Zone C

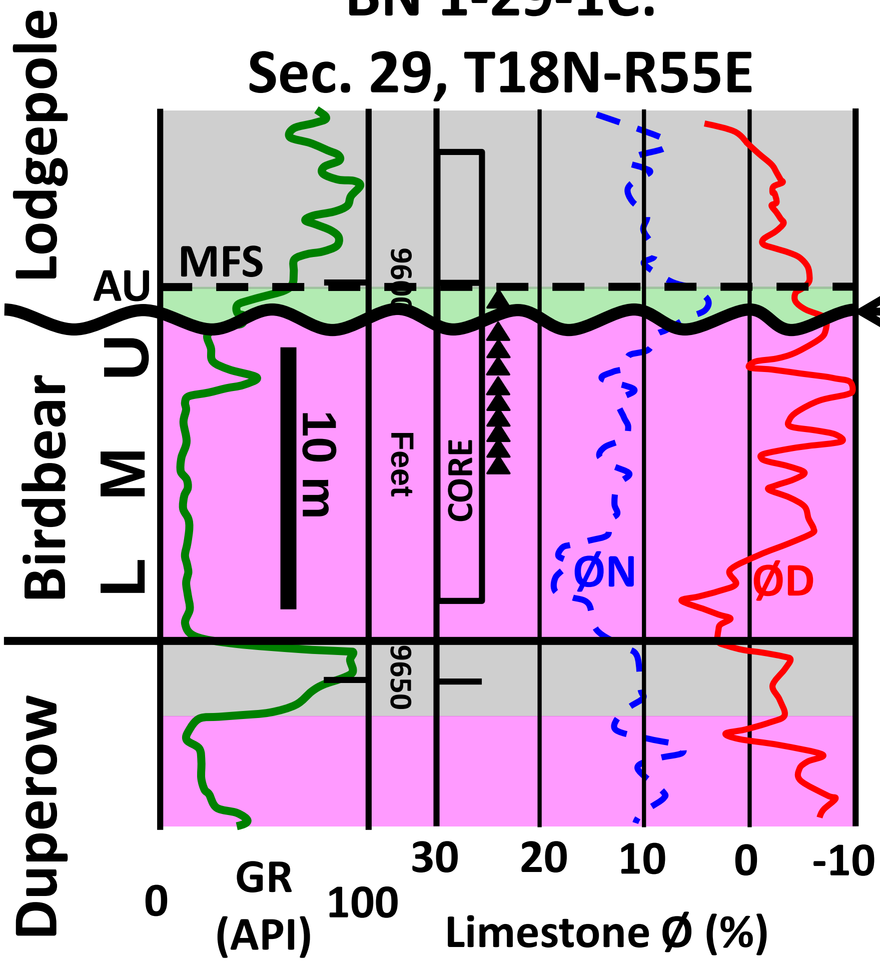



BN 1-29-1C:
Sec. 29, T18N-R55E
Lodgepole
Birdbear
Duperow
U
M
L
AU
MFS
9600
9650
10 m
Feet
CORE
ØN
ØD
Maximum Flooding Surface
Transgressive Lag Deposit
Acadian Unconformity
Diagenetic Zone C
Dolostone only
0
GR
(API)
100
30
20
10
0
-10
Limestone Ø (%)
Dominantly Dolostone
Skeletal-Fragmental
Limestone/Dolostone
▲ = Breccia
Sand, Silt and/or Clay-Rich Lithology

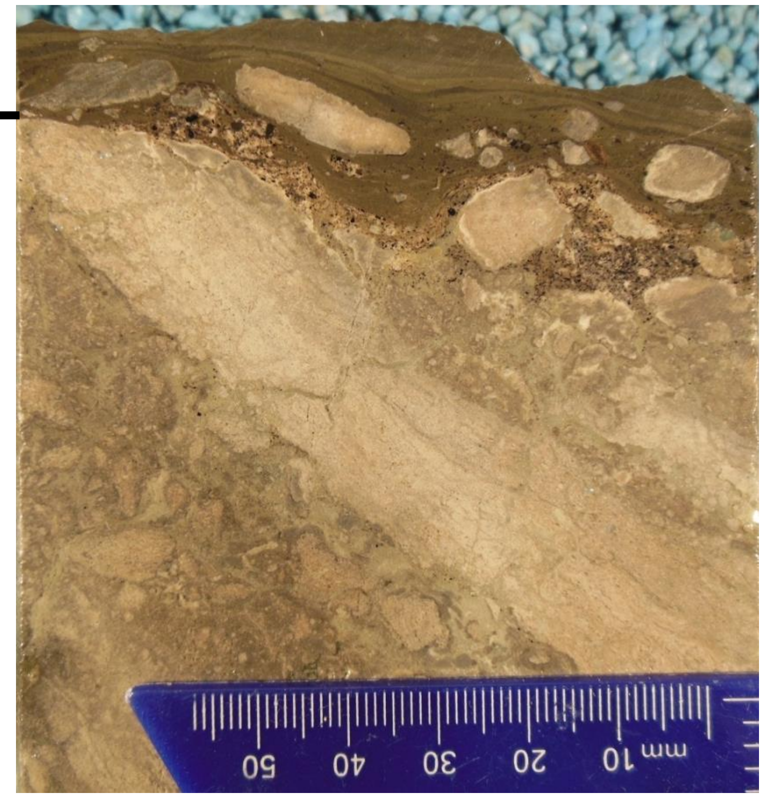
Basal Lodgepole: shaly, coral-crinoid limestone



BN 1-29-1C:
Sec. 29, T18N-R55E



Acadian Unconformity

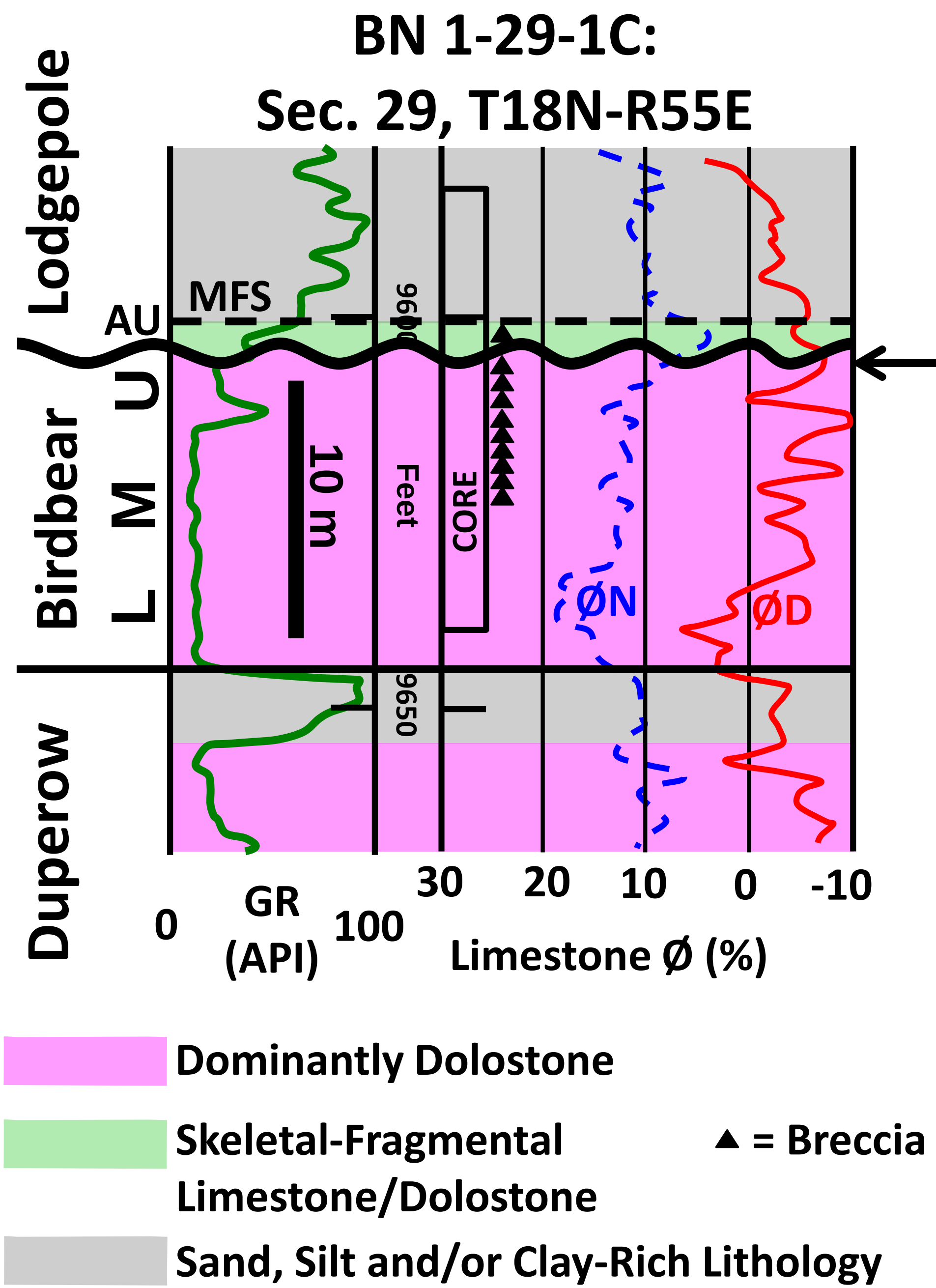


Dominantly Dolostone

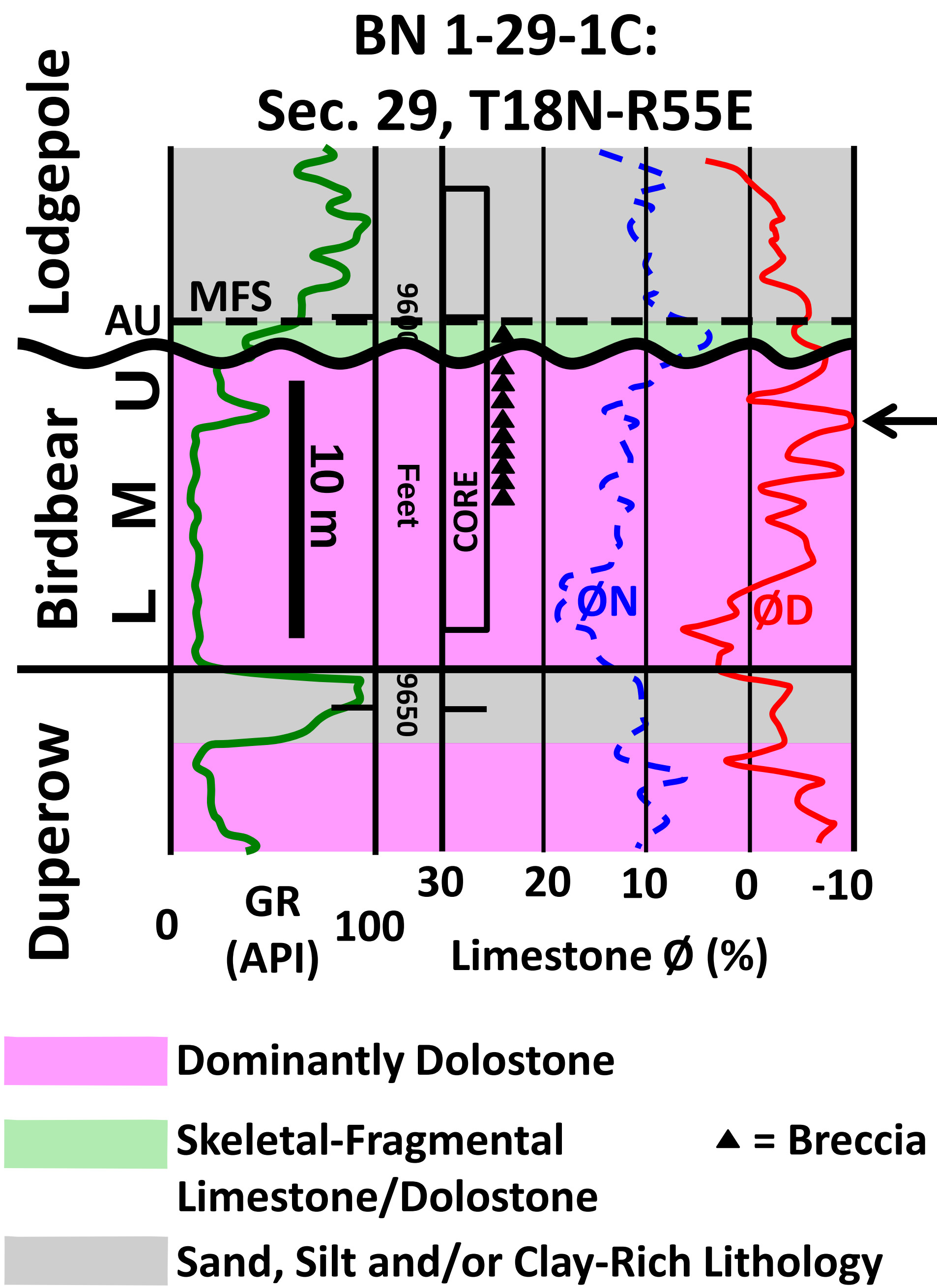
Skeletal-Fragmental Limestone/Dolostone

▲ = Breccia

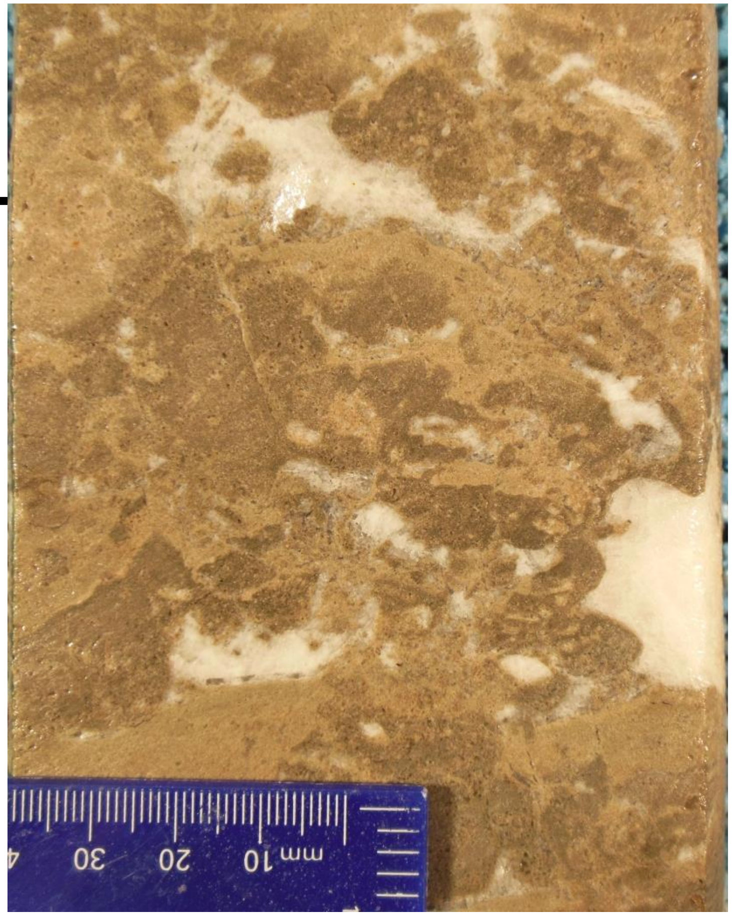
Sand, Silt and/or Clay-Rich Lithology

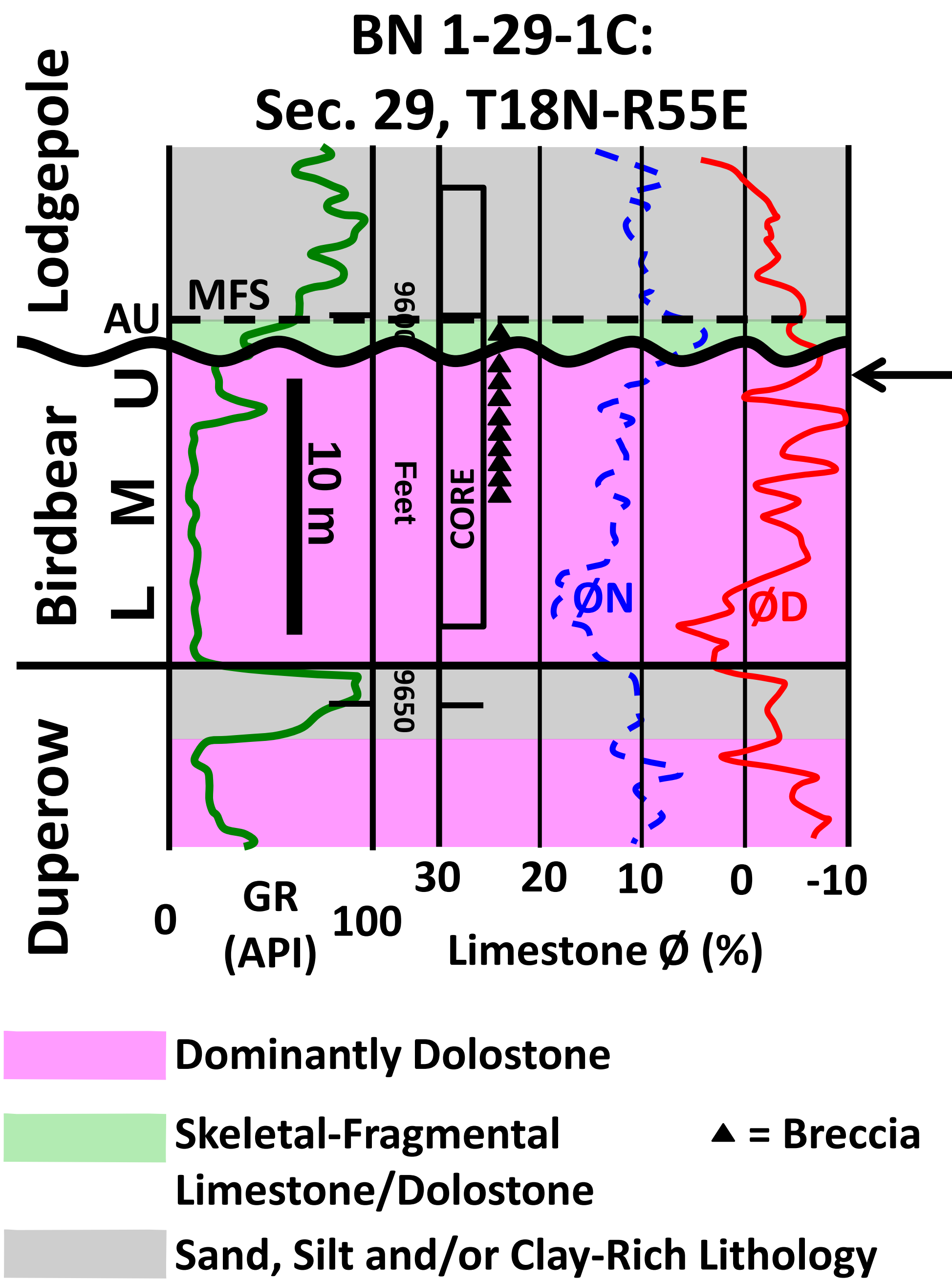


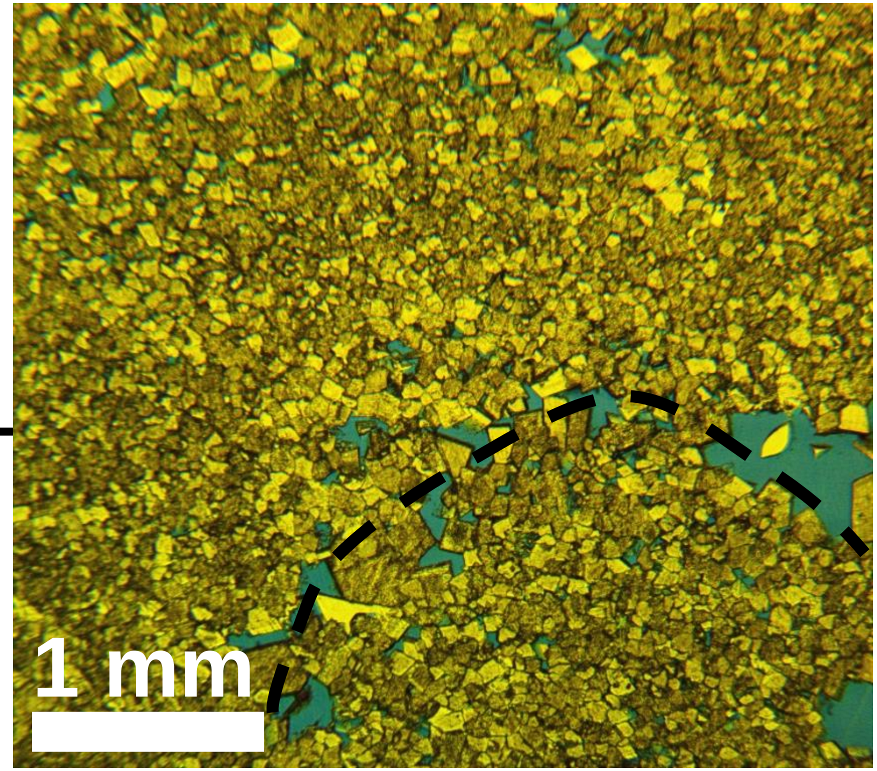
Birdbear solution breccia (dolostone)



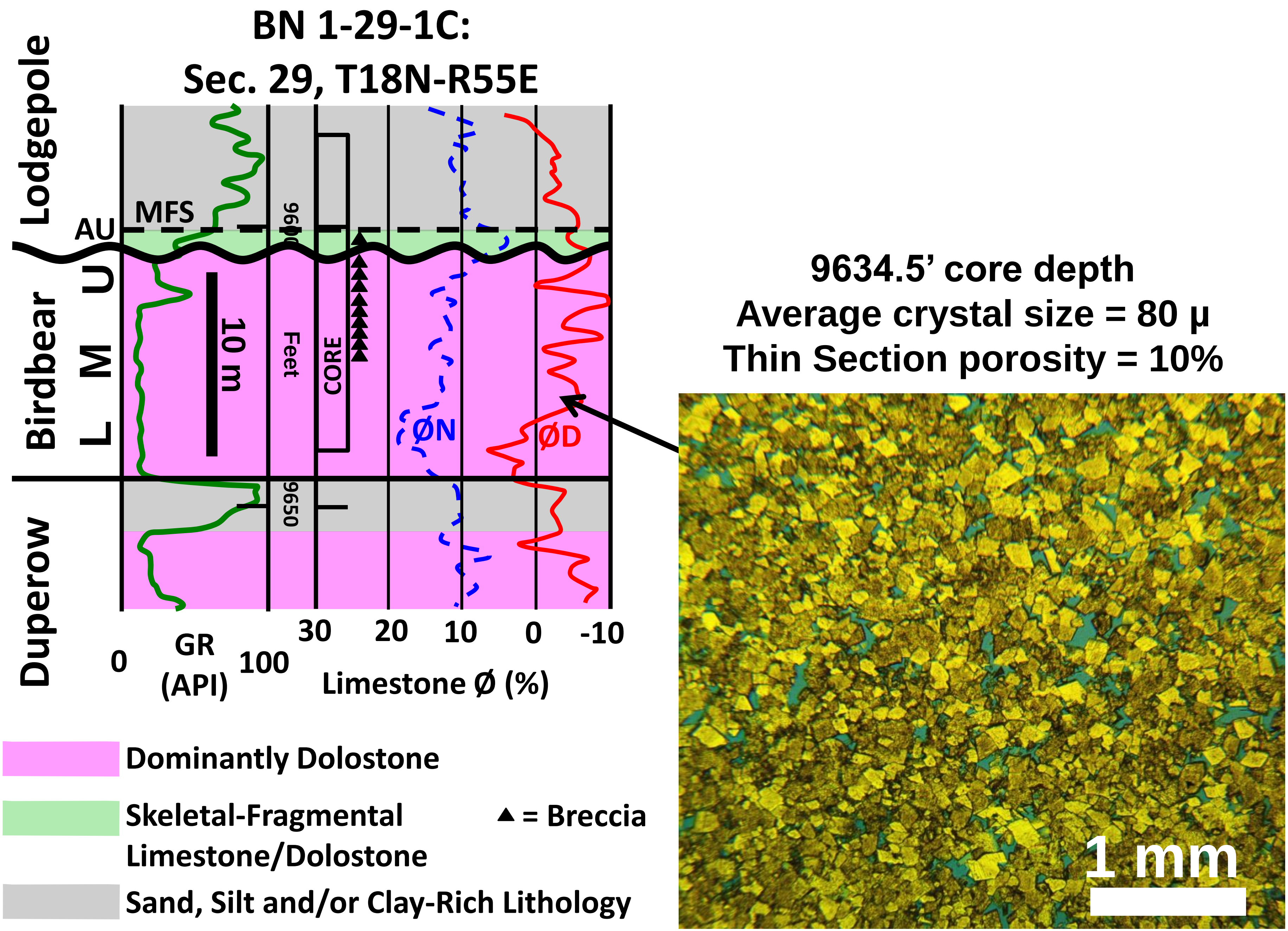
Anhydrite cement in solution breccia (anhydrite occurs throughout Birdbear)



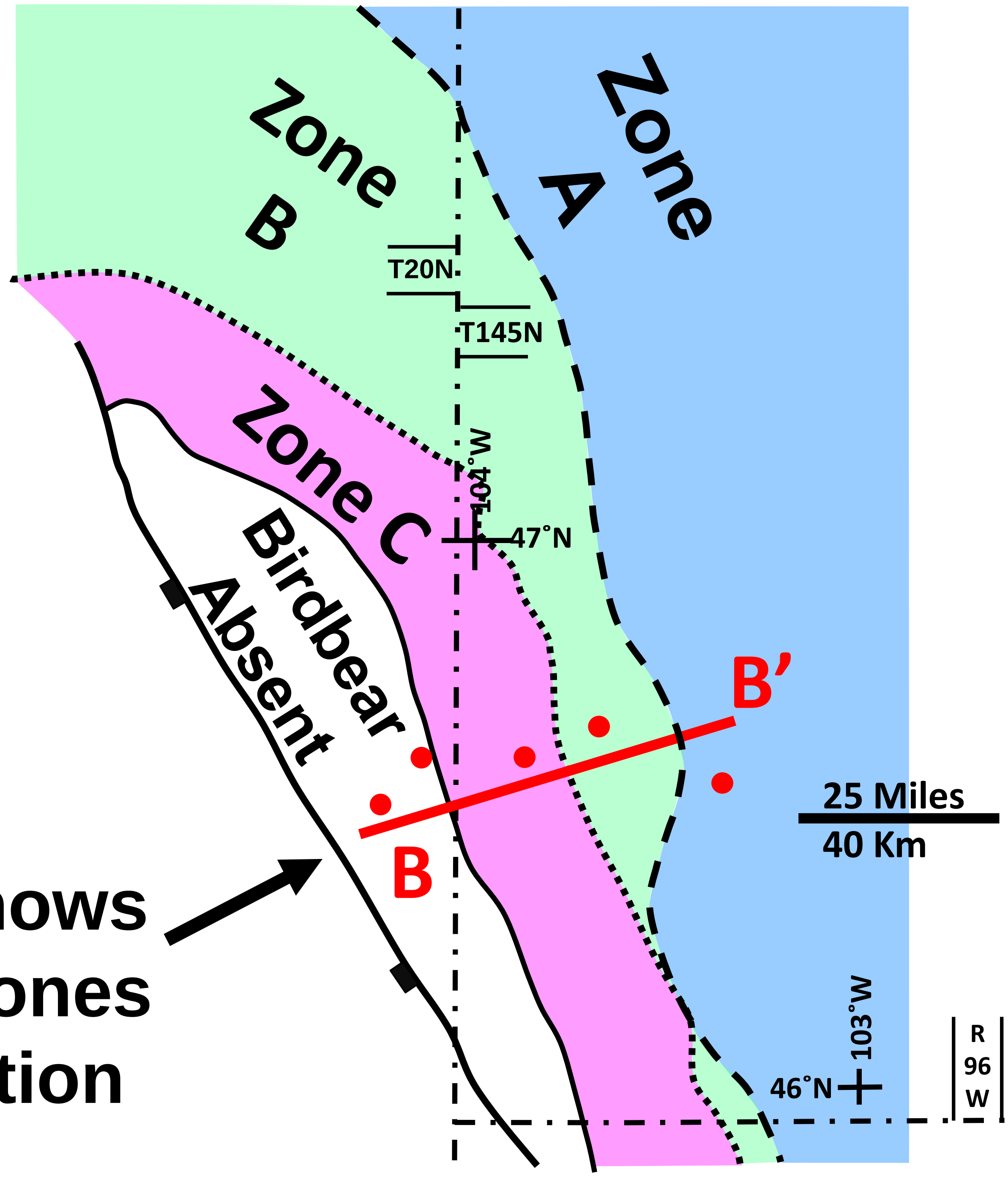




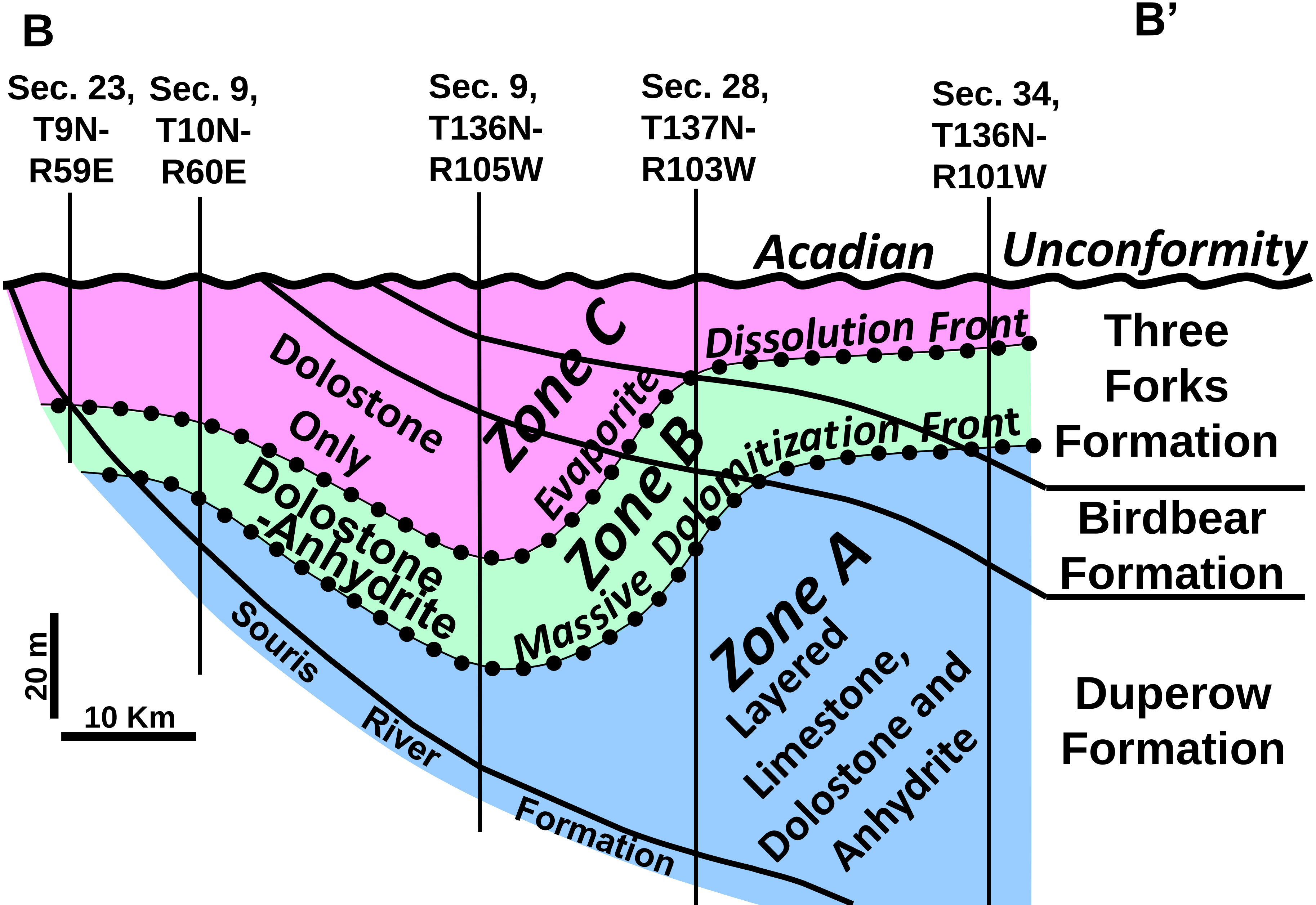
9607.5' core depth
Breccia with fabric-destructive dolomite; note breccia fragment outlined in lower-right corner of photo
Average crystal size = 100 μ
Thin Section porosity = 8%


BN 1-29-1C:
Sec. 29, T18N-R55E
Lodgepole
Birdbear
Duperow
AU
MFS
U
M
L
10 m
9600
9650
Feet
CORE
ØN
ØD
0
GR
(API)
100
30
20
10
0
-10
Limestone Ø (%)
Dominantly Dolostone
Skeletal-Fragmental
Limestone/Dolostone
Sand, Silt and/or Clay-Rich Lithology
▲ = Breccia
9634.5’ core depth
Average crystal size = 80 µ
Thin Section porosity = 10%
1 mm

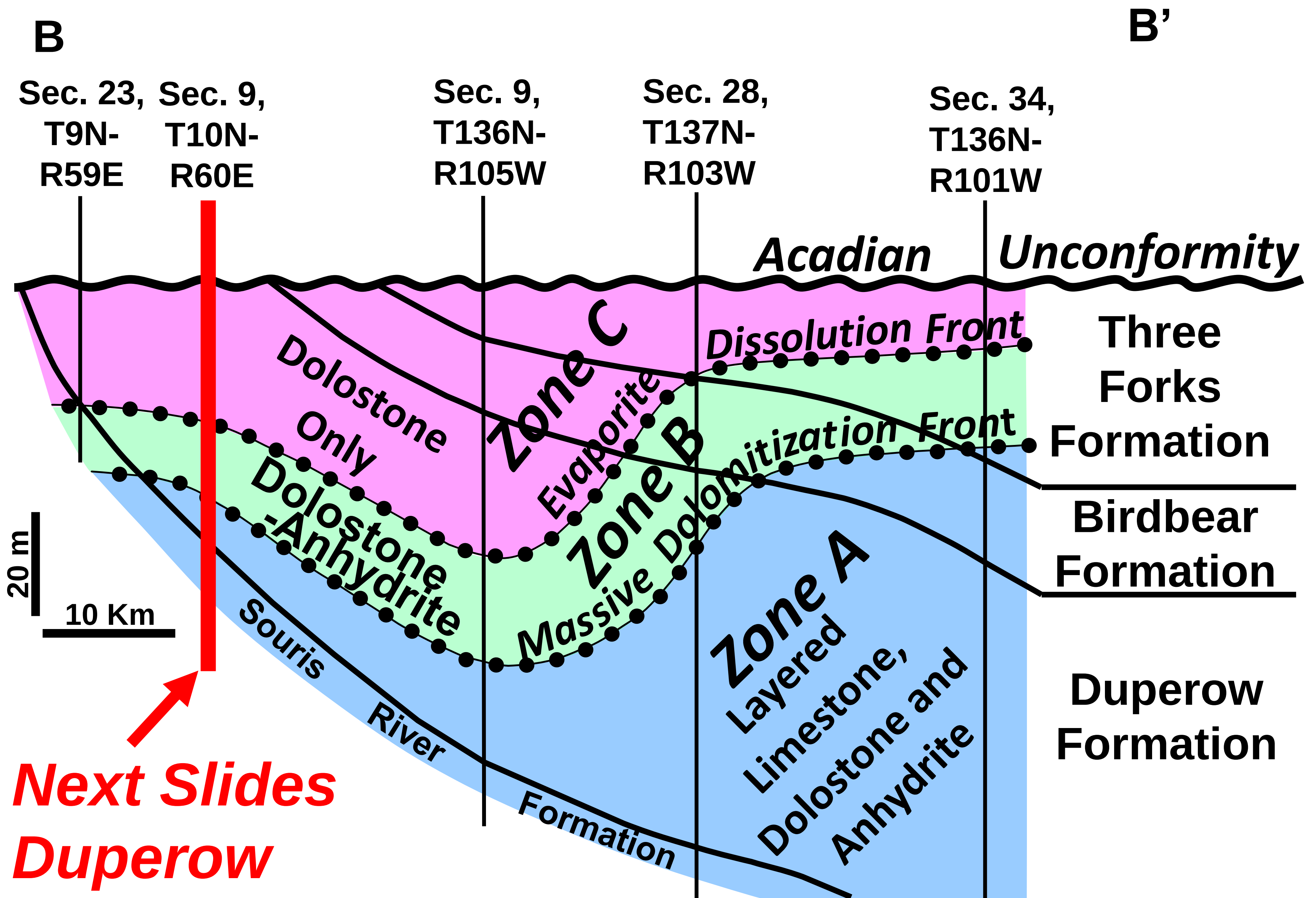
Birdbear Diagenetic Zones



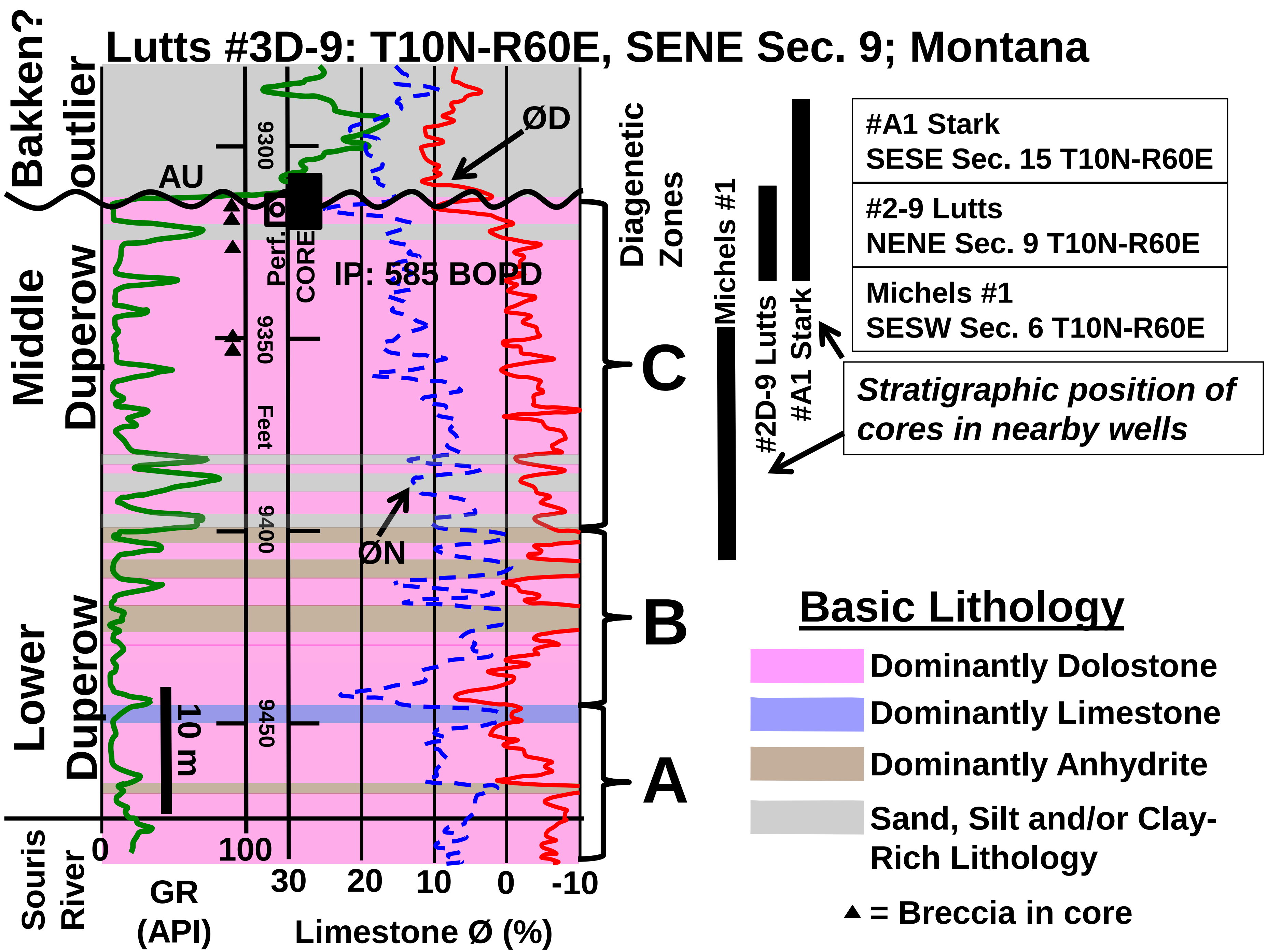
Next Slide shows Diagenetic Zones in Cross Section



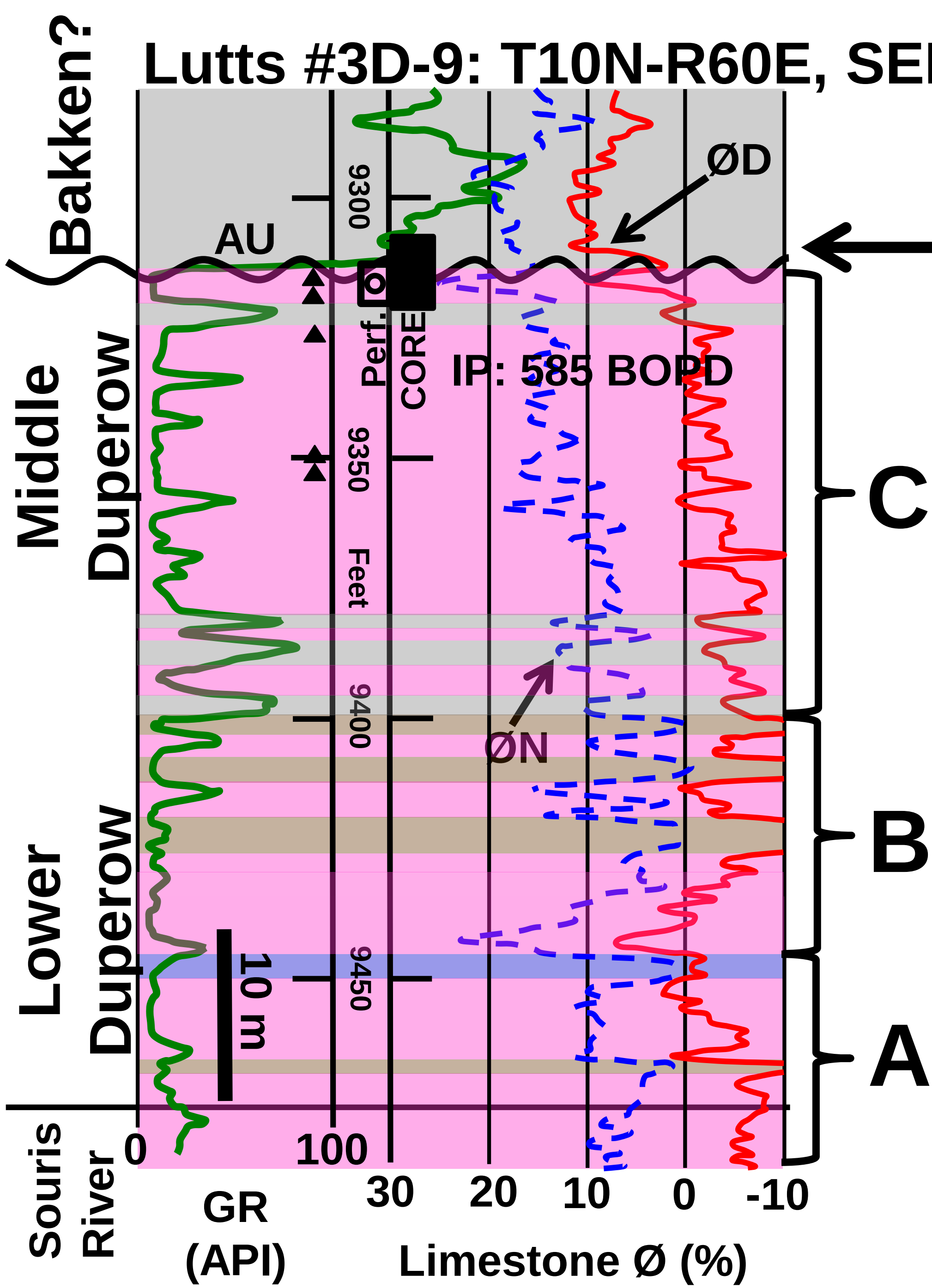
Note Scale; fronts are sub-parallel to Acadian Unconformity

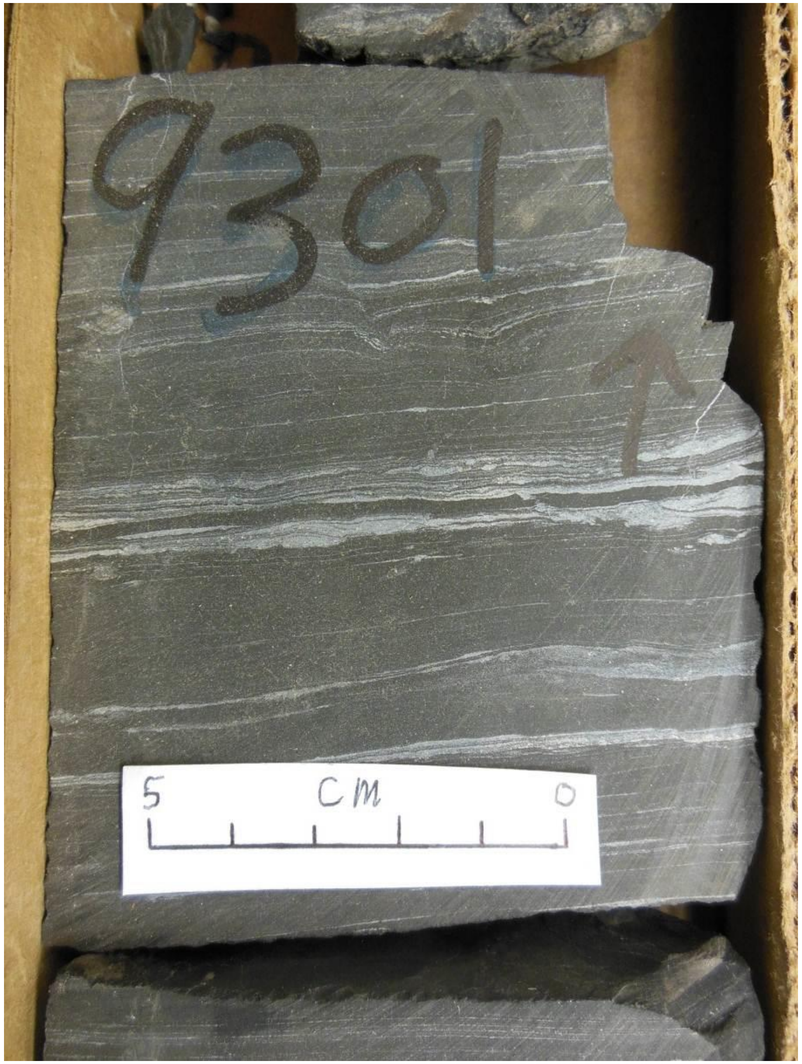

B
B'
Sec. 23, T9N-R59E
Sec. 9, T10N-R60E
Sec. 9, T136N-R105W
Sec. 28, T137N-R103W
Sec. 34, T136N-R101W
Acadian Unconformity
Three Forks Formation
Birdbear Formation
Duperow Formation
Zone C
Dolostone Only
Dissolution Front
Evaporite
Zone B
Dolostone -Anhydrite
Dolomitization Front
Massive
Zone A
Layered Limestone, Dolostone and Anhydrite
Souris River Formation
20 m
10 Km
Next Slides Duperow

Lutts #3D-9: T10N-R60E, SENE Sec. 9; Montana



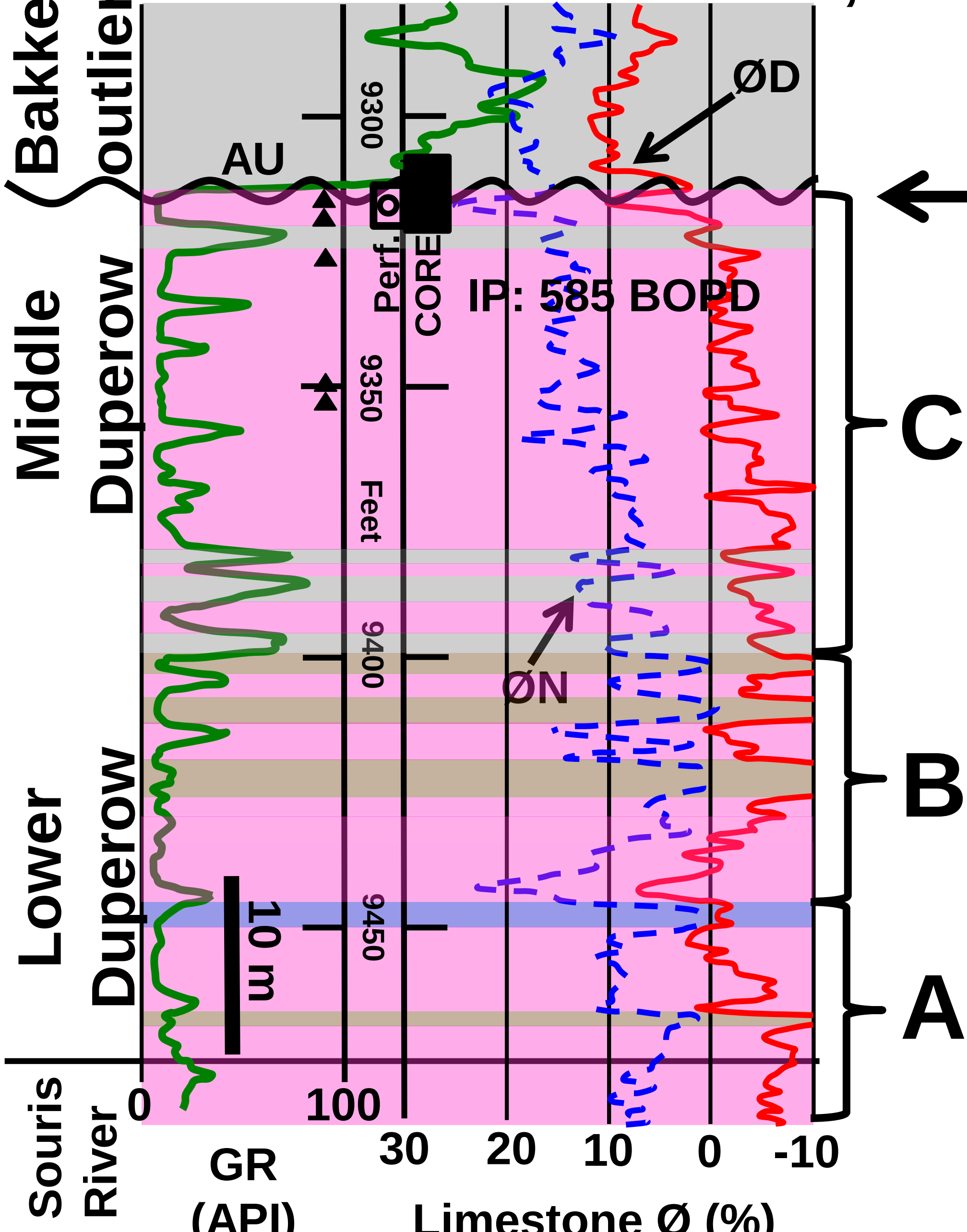
Lutts #3D-9: T10N-R60E, SENE Sec. 9; Montana

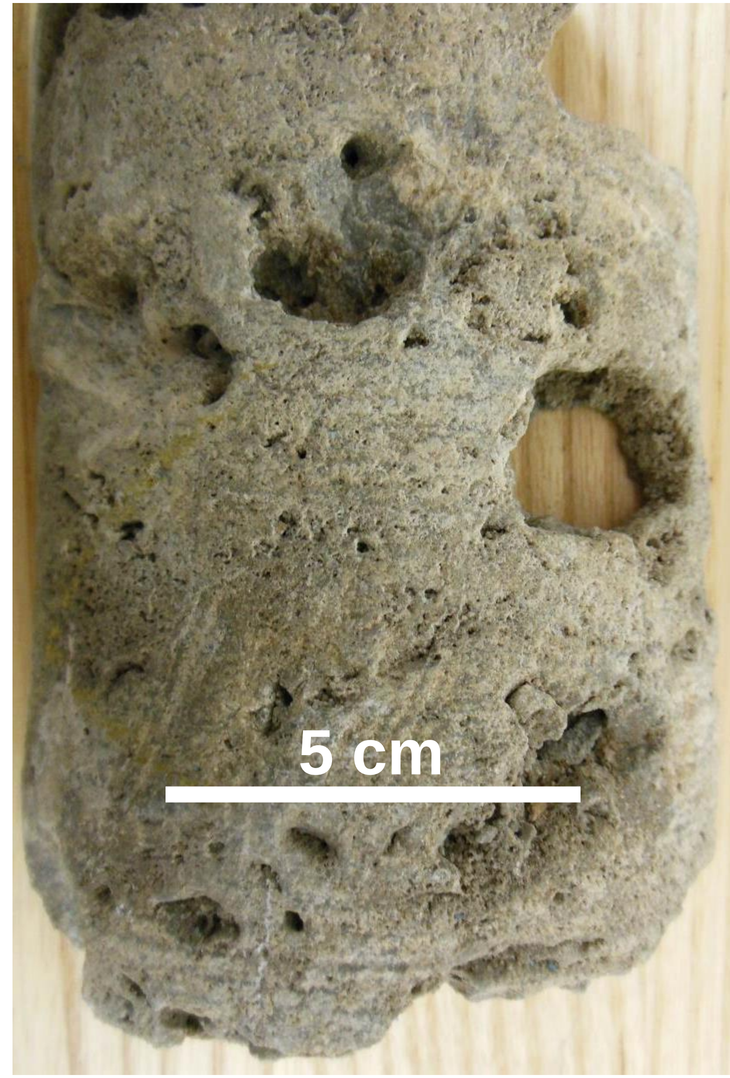




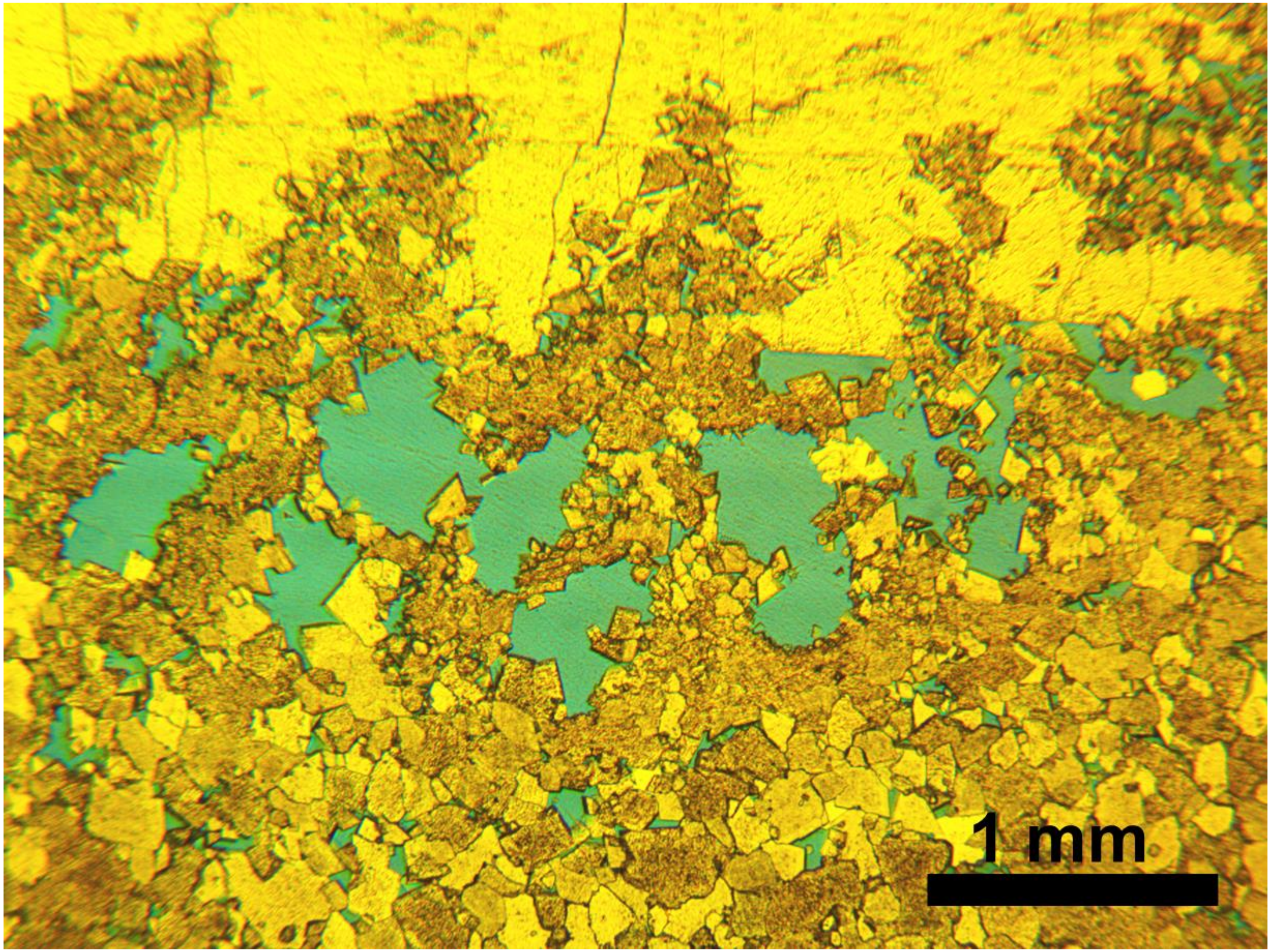
Laminated Shale
Upper Bakken (?) Outlier

Lutts #3D-9: T10N-R60E, SENE Sec. 9; Montana

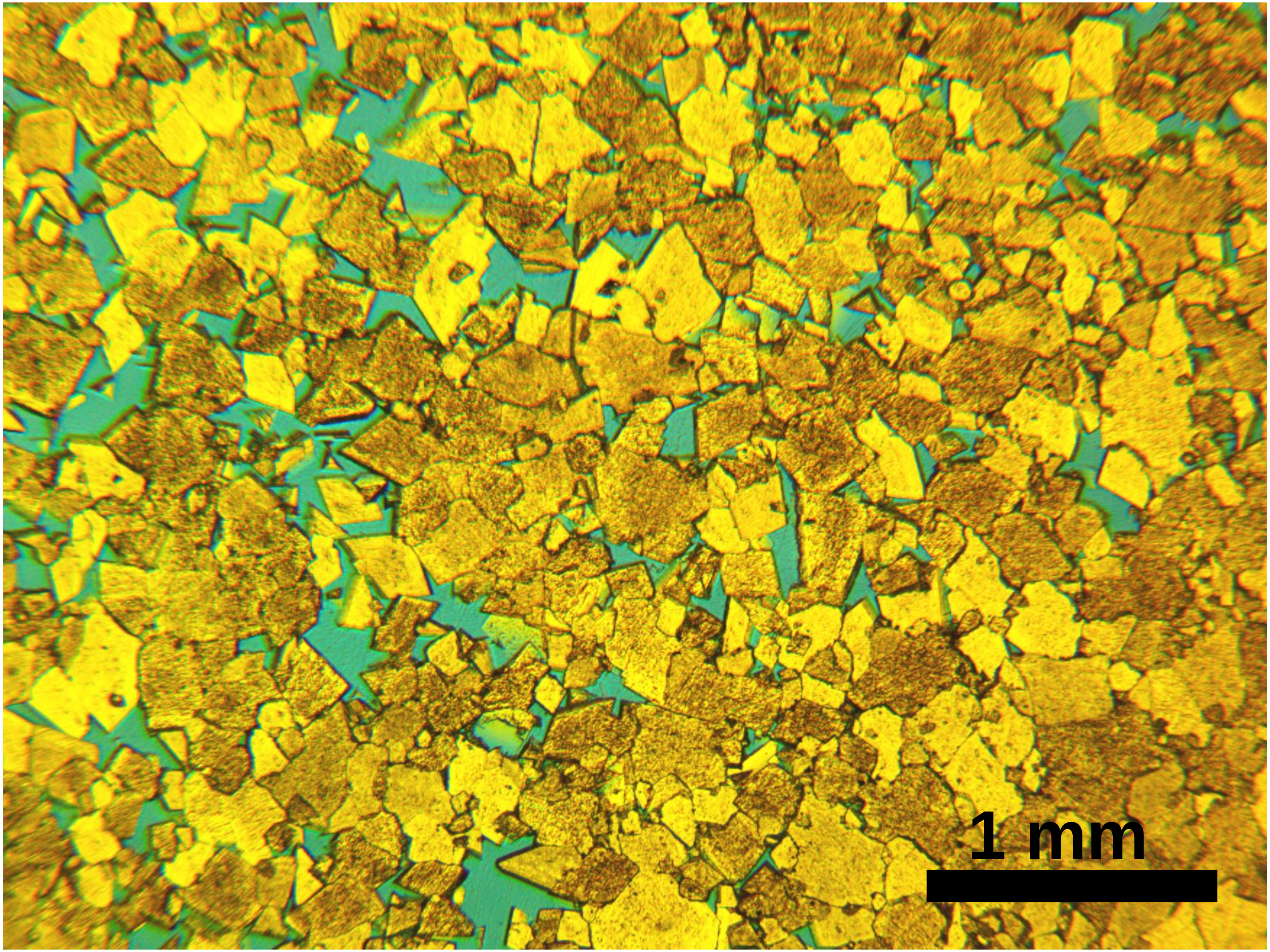




Dolostone breccia with solution porosity



Lutts #2-9_9271.5; 1.0 foot below unconformity. Coral replaced by fabric-destructive dolomite; anhydrite fills coral center



Lutts #2-9_9271.5_175 μ dolomite

Previous USA Studies
Massive Dolomitization

- **Rarely discussed in literature**
  - **Loeffler (1982) suggested mixing zone model for Birdbear massive dolostone in North Dakota**
  - **Smith and Dorobek (1989) inferred massive dolomitization for Birdbear-Duperow in central Montana caused by Mg brines generated during deposition of overlying Three Forks evaporite**
- ***Model discussed here differs from all previous models***

Stratigraphic Constraints on Timing for Basin-Margin Diagenesis in the Birdbear and Duperow

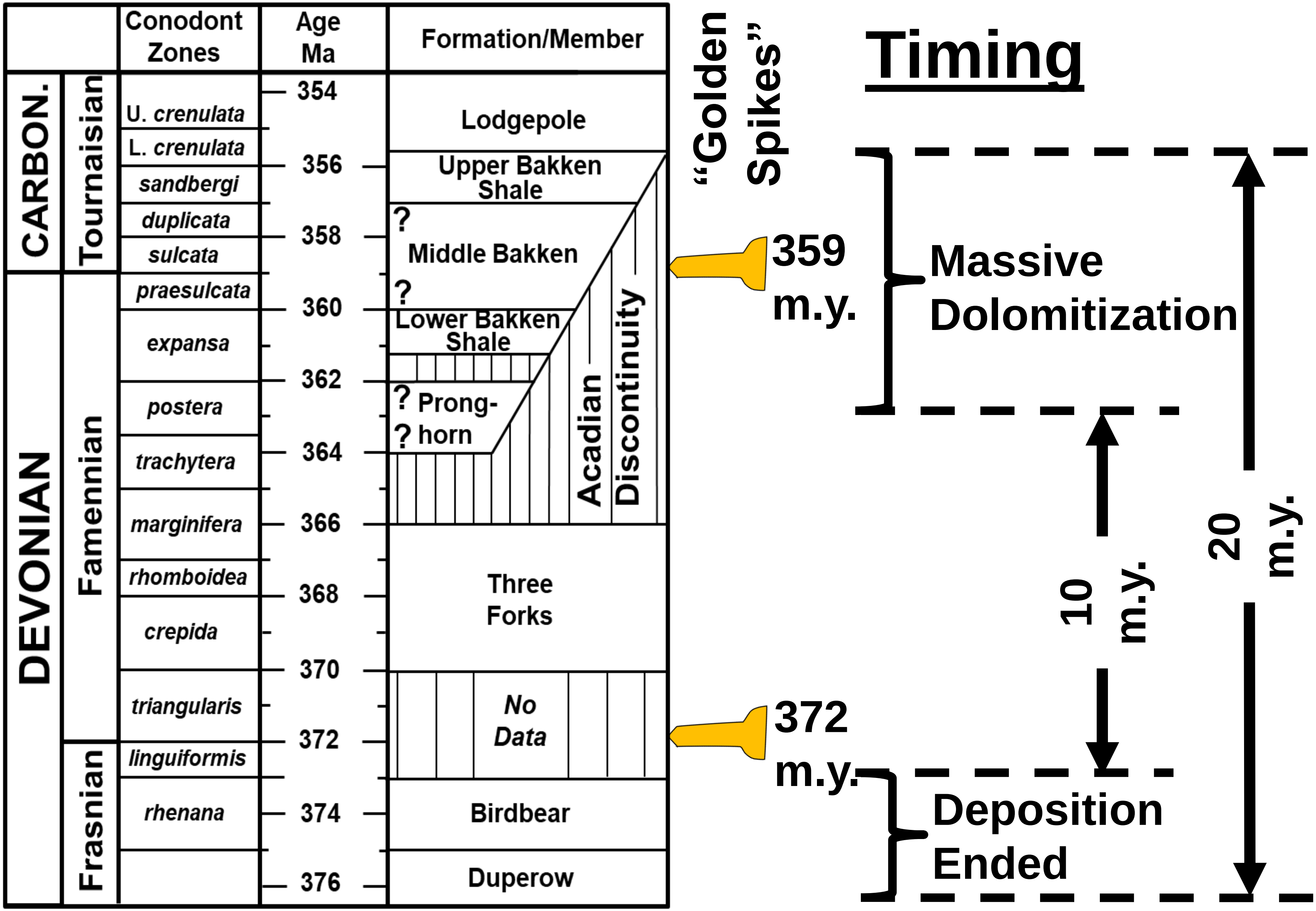
1. **Massive dolomitization occurred before Lodgepole deposition**
   - **No regional dolomitization in basal Lodgepole**
2. **Massive dolomitization and sub-karst dissolution occurred after most or all unconformity development:**
   - ***Massive dolostone and evaporite dissolution are sub-unconformity features;*** **they occur only in proximity to sub-unconformity areas**
   - ***Massive dolostone front and evaporite dissolution front are sub-parallel to the unconformity; they are sub-parallel to existing (final) unconformity***
   - ***Top-down diagenesis below unconformity***

Additional Stratigraphic Observations:

- **L. Pronghorn sandy dolostone in southwest North Dakota is a detrital deposit derived from erosion on Cedar Creek anticline (Skinner et al., 2015)**
- **L. Pronghorn sandy dolostone mineralogy is very similar to upper Three Forks sandy dolostone mineralogy**

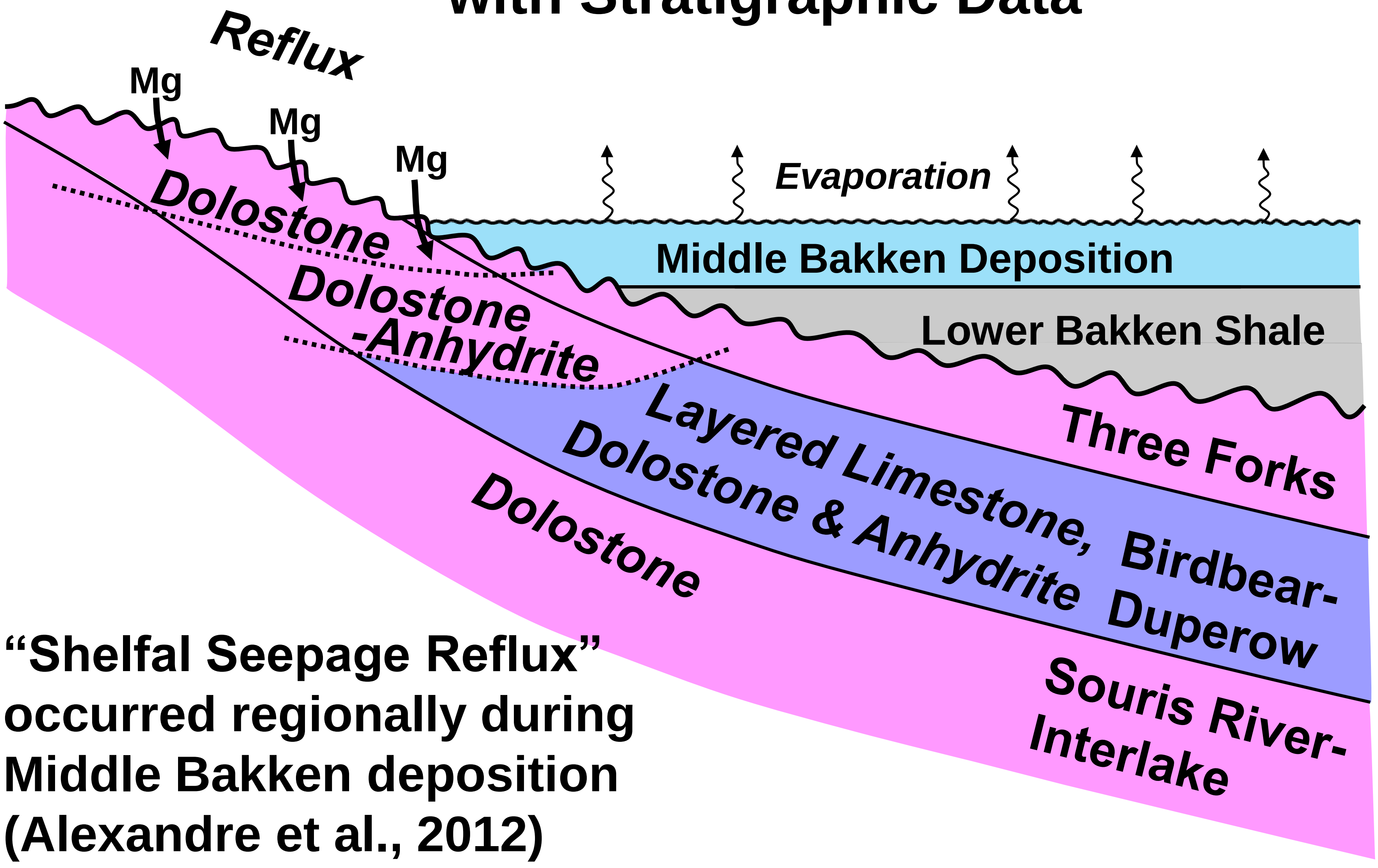
Stratigraphic Interpretations:

- **Lower Pronghorn deposition represents initial exposure of Cedar Creek anticline**
- **Most of the observed sub-unconformity Birdbear-Duperow diagenesis occurred after L. Pronghorn deposition (i.e., after removal of Upper Three Forks on Cedar Creek anticline)**
- **Most sub-unconformity diagenesis probably occurred during Bakken deposition**



Conodont Zones
Age Ma
Formation/Member
"Golden Spikes"
Timing
CARBON.
Tournaisian
DEVONIAN
Famennian
Frasnian
U. crenulata
L. crenulata
sandbergi
duplicata
sulcata
praesulcata
expansa
postera
trachytera
marginifera
rhomboidea
crepida
triangularis
linguiformis
rhenana
354
356
358
360
362
364
366
368
370
372
374
376
Lodgepole
Upper Bakken Shale
Middle Bakken
Lower Bakken Shale
Prong-horn
Three Forks
No Data
Birdbear
Duperow
Acadian Discontinuity
359 m.y.
372 m.y.
Massive Dolomitization
Deposition Ended
10 m.y.
20 m.y.

Dolomitization During Middle Bakken Deposition is Consistent with Stratigraphic Data



"Shelfal Seepage Reflux" occurred regionally during Middle Bakken deposition (Alexandre et al., 2012)

Conclusions

1. Regional evaporite dissolution formed below an "evaporite karst" that developed during development of the Acadian Unconformity

- **Mappable**
- **Dissolution up to 50 m below unconformity**

Conclusions

2. Stratigraphic constraints indicate that massive dolostone in the Birdbear and Duperow formations formed as a result of one or more diagenetic events that occurred after unconformity development and before Lodgepole deposition

- **Dolomitization front sub-parallel to unconformity**
- **Massive dolostone up to 70 m below unconformity**
- **Dolomitization occurred during Bakken deposition**
- **Speculative conclusion that massive dolomitization occurred during Middle Bakken dolomitization**
- **Dolomitization 10-20 million years after deposition is responsible for “massive” characteristics**

END

Acknowledgements:

- **Cores were examined at the USGS and NDGS**
- **Thin sections collected from these studies are on file at these organizations**
- **NDIC web data base indispensable**